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DISPERSION, MIXING AND INTENTIONAL IGNITION OF HYDROGEN IN THE DARLINGTON REACTOR VAULT

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ABSTRACT

The present report reviews the Darlington Safety Report (DSR) which has been used as basis for decisions regarding intentional ignition in the Darlington reactor vault. The validity of the assumptions in the DSR regarding mixing of contents is assessed and possible hydrogen release scenarios, specific to the Darlington reactor vault, are examined. The combustion analysis in the DSR "vent code" calculations are reviewed in the light of existing state of the art information on high speed turbulent flames and transition to detonation. Limitations of the "vent code", in this context, are identified and improvements recommended.

RÉSUMÉ

Le présent rapport examine le rapport de sûreté de Darlington qui a servi de base pour les décisions concernant l'inflammation délibéré à l'intérieur du bâtiment du réacteur. La validité des suppositions du rapport de sûreté de Darlington au sujet du mélange du contenu est évaluée et des scénarios possibles de rejet d'hydrogène, particuliers au bâtiment du réacteur de Darlington, sont étudiés. L'analyse de combustion dans les calculs du "code de ventilation" du rapport de sûreté de Darlington est examinée à la lumière des données de pointe disponibles à propos des flammes turbulentes à grande vitesse et de la transition vers la détonation. Les limitations du "code de ventilation", dans ce contexte, sont déterminées et des améliorations sont recommandées.

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A. INTRODUCTION

In the aftermath of the accidents at Three Mile Island in 1979 and at Chernobyl in 1986, the safety of nuclear power plants has received a great deal of public attention. Among the various possible accident scenarios, those that pose a direct threat to containment integrity are considered the most hazardous in that they constitute the most serious ultimate consequences to the public. In this category of accidents would fall steam explosions and hydrogen combustion consequent to molten fuel-coolant interaction. Hence prevention and control of the likelihood of such accidents are of primary importance. The present report deals exclusively with the second of these events namely hydrogen combustion in the context of the Darlington reactor vault.

In certain accident scenarios, the amount of hydrogen released can be sufficiently large to result in the formation of a combustible mixture inside the Darlington reactor vault. To mitigate the effect of a delayed accidental ignition of this combustible mixture, it is proposed to install igniters inside the reactor vault to ensure early ignition. The rationale behind intentional early ignition is to initiate combustion as soon as the mixture reaches its flammability limits. Thus, the build-up of hydrogen to "dangerous" concentration levels for the mixture in the vault is prevented. The combustion of a near-limit mixture by early intentional ignition would be rather "benign" and would pose no threat to containment integrity. An analysis of the pressure transients resulting from intentional ignition inside the Darlington reactor vault has been carried out by Ontario Hydro and documented in the Darlington Safety Report which was submitted to AECB. The present report describes the results of an independent review of the Darlington Safety Report (DSR)[1].

B. ASSESSMENT APPROACH

The mitigative effectiveness of a given intentional ignition situation depends strongly on the accuracy of the estimate of hydrogen distribution and of the burning rate of the mixture in the vault. Thus before evaluating the mitigative effectiveness of proposed methods, the accuracy of the predicted hydrogen distribution and of the assumed burning rate of a combustible mixture must be assessed. If the hydrogen distribution is known, then the igniters can be properly placed to ensure ignition once the mixture reaches its flammability limit. Knowledge of the burning rate is essential for estimating the pressure transients subsequent to ignition. In the ideal case of perfect mixing, the hydrogen concentration will be uniform throughout the vault volume. Thus a single igniter would be sufficient and its location inside the vault is immaterial since the hydrogen distribution is homogeneous. Also, if the hydrogen concentration is uniform, then ignition would occur as soon as the flammability limit is reached. Subsequent burning of the near-limit mixture is very slow in general. Thus the pressure transient is insignificant. This would be true even for an unvented vault since the very slow burning of near-limit mixtures would permit substantial heat losses to occur. The peak overpressures generated would thereby be much lower than the adiabatic value, which in itself is very small for near-limit mixtures. However, in actual fact, the ideal case mentioned above cannot, in general, be realized.

C. THE DARLINGTON SAFETY REPORT - ASSUMPTIONS AND RESULTS

1. Mixing

The key assumption made in the Darlington Safety Report (DSR) is that perfect mixing can be achieved, hence the hydrogen concentration is uniform throughout the vault at all times. Thus combustion is initiated by the igniters when the mixture composition reaches the boundary of the "assured ignition" curve of the Tayco igniters (Figure 1) which is slightly narrower than the flammability limit (e.g. the assured ignition curve requires a slightly higher hydrogen concentration than the lean flammability limit). To investigate the question of non-uniformities in the hydrogen distribution it is assumed in the DSR that the maximum hydrogen difference that can occur is 3%. It is presumed that uniform mixing throughout the vault is still achieved but that the hydrogen concentration between the igniter location and the uniform mixture away from the igniter can be 3% different. In essence, this 3% gradient assumption translates to mean that the mixture is 3% richer in hydrogen than that indicated by the assured ignition curve of the Tayco igniter (Figure 1).

The assumption of uniform hydrogen distribution in the DSR is based on the work done at WNRE[2] and EPRI-HEDL[3]. The WNRE mixing studies were carried out in a small vertical cylindrical vessel (0.46 m diameter and 0.65 m long) connected to a pipe (0.05 m diameter by about 1 m long) as illustrated in Figure 2. Flow visualization by schlieren photography was also carried out in a scaled-down vessel-pipe assembly (i.e. a rectangular vessel 23 $cm \times 23\ cm \times 30\ cm$ connected to a 2.5 diameter $\times$ 0.45 m long pipe) as illustrated in Figure 3. Helium and carbon dioxide were used as the test gases.

The main conclusion of the WNRE study is that the forced recirculation caused by the fans help complete mixing for the whole system. However, the WNRE mixing studies were carried out on too small a scale and too simple a geometry to satisfy either geometrical or dynamic similarity requirements. Hence the WNRE results cannot provide the baseline for meaningful extrapolation to the real situation of the Darlington reactor vault.

The second justification of uniform mixing assumed in the DSR is based on the EPRI-HEDL mixing studies. A series of seven dispersion and mixing tests were carried out at the Hanford Experimental Development Laboratory under the auspices of EPRI. The tests were intended to simulate the dispersion and mixing of hydrogen-steam with air in the lower compartment of an ice condenser containment. The hydrogen-steam release in containment was postulated to correspond to a break of i) a 5 $cm\ dia$ pipe connected to reactor coolant systems (horizontal choked jet) and ii) a 25 $cm\ dia$ rupture disc on a pressure relief tank (slower release directed upward).

The HEDL simulation tests were conducted in a one third scale containment systems test facility (CSTF). These tests were specifically designed to simulate the geometry of

the lower compartment of an ice condenser reactor containment built in the USA. The hydrogen-steam release for both scenarios was simulated with a discharge of helium-steam into air (one exception: hydrogen-steam into nitrogen). The release was scaled according to geometric and Froude number scaling. This led to one horizontal and one vertical discharge nozzle, typically 7.8 *cm dia* with a jet velocity of 200 *m/sec*. The conditions of the jet from the horizontal and vertical nozzles were claimed to be scaled to simulate both rupture scenarios.

The authors of the HEDL tests draw the following conclusions. They claim that the compartment is well mixed with maximum concentration differences less than 3 volume percent during the source release from a horizontal pipe or a vertical vent. The degree of mixing did not appear to be strongly dependent on source jet release orientation. Gas entrainment by the high velocity jet was the dominant mixing process during the jet release period. The test compartment was well mixed by natural convection after termination of the source gas for all cases; the forced air recirculation decreased the time required for good mixing. Finally, helium was considered to be a valid simulant for hydrogen in these hydrogen mixing and distribution tests.

After a thorough study, we have concluded that the HEDL tests are also not applicable to the Darlington situation for the following reasons:

1) The geometry of the Darlington reactor vault, the forced convection flow pattern, the distribution of equipment and plumbing are all totally different from that of the HEDL test chamber. Thus the most basic requirement for scaling of test results, namely that of geometric similarity, is missing between the HEDL tests and the Darlington vault.

2) There is no dynamic similarity between the flow parameters in the HEDL experiments and in the postulated Darlington release source flow fields. Since the source flow parameters for postulated accident scenarios in the Darlington reactor vault can take on a wide range of Froude, Reynolds and Schmidt numbers and the HEDL tests were based on a limited range of these numbers, the HEDL test results are not applicable to the Darlington reactor vault.

3) The location of the source in the HEDL experiments was changed only slightly. In the Darlington situation, the source location can be in a number of different places with different local environments. This will greatly change the forced and natural convection flow pattern and thus the hydrogen mixing.

It must be pointed out that even in the case of the HEDL tests, large actual concentration gradients were observed. The HEDL tests show a 3% variation as an actual absolute compositional change (i.e. say test HM-6 an actual change between a 3% *He* by volume mixture and a 6% *He* by volume mixture) which represents a 50% fluctuation for a baseline of the 6% *He* concentration by volume, or conversely a 100% fluctuation for a baseline of 3% *He* concentration by volume.

It is worthwhile to point out additionally that the 3% difference between the maximum and minimum concentrations was exceeded in tests HM-1 and HM-2 where the differences were 3.8% and 7.8%, respectively. In the HEDL report, these values were dismissed as anomalous in what they did not, it is claimed, represent typical reactor plant "postulated accident conditions". It is not clear why this is so.

Even for the HEDL tests the concentrations and differences measured for *He* were on the "dry basis". This would only be meaningful in terms of scaling if the data were non-dimensionalized. It is suggested to non-dimensionalise the differences in helium concentrations measured throughout the vessel in terms of the jet exit concentration, on a mole fraction basis. Only in this case would meaningful scaling be achieved and the scaling would be linear if geometric and fluid mechanical similarity were preserved in the scaling process.

A detailed analysis of the HEDL mixing studies is given in Appendix A. We feel therefore that neither the WNRE nor the HEDL mixing studies can be used to justify the assumption of uniform mixing in the DSR. Additional studies both experimentally and numerically are necessary for proper placement of the igniters and analysis of the subsequent combustion processes.

2. Combustion

2.1 DSR Vent Code Combustion Assumptions

2.1.1 Combustion of Fully Mixed Contents

The development of pressure inside the reactor vault is estimated by the use of the VENT CODE developed by WNRE. It is a one-dimensional code valid for slow burning rates so that pressure waves can be ignored. It assumes a spherical geometry with central ignition and if venting is allowed, the vent area is assumed to be uniformly distributed on the outside of the spherical shell to retain a spherically symmetrical flow venting of the unburned gases. It is essentially the same as the Bradley and Mitcheson model. Although the DSR points out that "spherical confinement with central ignition produces the fastest combustion transients with the highest peak pressures for a given mixture", this is not true for the case of multiple ignition points since the total flame area and its rate of growth exceed that of a single spherical flame kernel. Since it is clear that a number of Tayco igniters are to be used in reality, the pressure transients must be evaluated for multiple ignition sources instead of a single source.

The question of non-uniformities was investigated by assuming a maximum hydrogen gradient of 3% in the absence of forced convection by the vault cooler fans. In other words, it is assumed that the hydrogen concentration away from the igniters could be 3% higher than that at the igniters (which essentially see a concentration corresponding to the assured ignition curve). It is presumed that uniform mixing throughout the vault is still achieved other than the 3% difference in H_2 concentration between the igniter location and away from the igniter location. In essence, the 3% gradient

translates to mean that the vent code is used to calculate the pressure transients in the vault due to combustion of a mixture 3% richer in H_2 than that indicated by the assumed ignition curve of the igniter. The analytic assumptions used by the vent code in the combustion analysis are summarized in Table I. The base or reference curve in Figure 4 is based on the initial condition of 80 *kpa* and 353°K in a spherical volume of 13571 m^3 with central ignition and distributed vent area of the spherical shell of the volume of 183.64 m^2. The mixture composition of the reference case in Figure 4 is not stated explicitly in the report, however it can be inferred that the percentage of H_2 and steam follow that governed by the assured ignition curve of Figure 1 and that the total gas inventory inside the vault is 331 *kmol* and out of that 146 *kmol* is hydrogen. Regarding the 3% gradient to account for the mixture non-uniformity, it is presumed that a narrower assured ignition curve 3% richer in H_2 is used. The resultant vent code calculation is shown in Figure 5 following the mixture composition of 3% richer in H_2, than the corresponding assured ignition limit concentration. For greater than 30% H_2, the static pressure load exceeds the 197 *kpa* limit.

2.1.2 Combustion of H_2-Rich Pockets

In a second type of sensitivity analysis, the effect of a local pocket of H_2 rich mixture is analyzed. The analysis is based on the worst H_2 source term (146 *kmol*). Steam is allowed to condense and an equal volume of air is then drawn in. It is assumed that the air drawn in mixes with the H_2 to form a stoichiometric mixture which is considered most sensitive (from the point of view of a maximum flame speed this is not true). The stoichiometric H_2-air plus team then forms the pocket. The pocket mixture composition is calculated as follows: the total gas inventory is 331 *kmol* with 146 *kmol* being H_2 and the rest (i.e. 185 *kmol*) being steam. If one assumes 90% of the steam to be condensed out and hence 10% (i.e. 33 *kmol*) left, then 152 *kmol* of air will be drawn in to replace the condensed steam. With 152 *kmol* of air there is 31.92 or $\sim$ 32 *kmol* of O_2 which requires 64 *kmol* of H_2 to form a stoichiometric $H_2 - O_2$ mixture. Thus the pocket is assumed to consist of 152 *kmol* air plus 64 *kmol* hydrogen and $64/146 \times 33 = 14$ *kmol* of steam making a total of 230 *kmol* of gas. The volume percentage of the vault this pocket occupies would then be 230 *kmol* of gas. The volume percentage of the vault this pocket occupies would then be $230/331 = 69.5\%$. The above detailed explanation of how to get the mixture composition in the pocket is represented by case I in Table II. Other cases with different amounts of steam being condensed out (or amount of steam that remains) are also shown in Table II. It should be noted that it is equally feasible that the volume of air drawn to replace the condensed steam simply mixes with the non-condensible H_2 to form a stoichiometric H_2-air mixture without any steam dilution. In fact, this is more likely the case since only H_2 is left in the void when the steam condenses out and air is being drawn in rather than a H_2 plus steam mixture. Without any steam dilution, the stoichiometric H_2-air pocket will be much more sensitive and prone to flame acceleration and transition to detonation. In calculating the pressure transient due to the combustion of the pocket, the vent code is used but a less conservative case (compared to the reference case) is calculated. The gas pocket is assumed to be ignited at the side (not central ignition) and burnt gas venting (instead of unburnt gas venting as in the reference case)

is considered. The result is shown in Figure 6. It would be more consistent to use the same set of assumptions as used in the reference case (Figure 4). This undoubtedly will lead to a much higher pressure development. Furthermore, as previously pointed out, even the reference case assumes only a single ignition point in contradiction to the actual case where a number of Tayco igniters are installed within the vault volume.

The safety report also brings in the argument that is is impossible to form large pockets of a uniform hydrogen-air-steam mixture of stoichiometric composition due to poor mixing. The EPRI Hanford mixing experiments are quoted to indicate that component gas compositions are highly dynamic during the transient gas filling period and that local gas composition fluctuates rapidly. Yet, the same Hanford exeriments are used earlier to justify that uniform mixing is achieved rapidly to permit the Tayco igniters to burn an essentially uniform mixture as the composition enters the "assured ignition cure" from outside the flammability limit. In conclusion, even based on the assumption of a burning velocity of 10 times the corresponding laminar flame value, the pressure transient analysis in the safety report using the vent code does not represent the most conservative estimate as claimed.

2.1.3 Combustion Rate Assumption

Perhaps the more serious assumption in the combustion anaylsis is the use of a burning velocity 10 times the corresponding value for a laminar flame. It is well established that large scale turbulence as produced in the wake of large flow obstacles (e.g. pipes and equipment) can give rise to significantly higher burning rates other than the assumed value of 10 times the laminar burning velocity. The current state of art falls short of giving a quantitative correlation between the burning rate and the turbulence intensity and scales. However, the work at McGill[4] over the past decade has provided an upper bound for the burning velocity as a function of hydrogen concentration for hydrogen-air mixtures at ambient initial conditions (i.e. atmospheric pressure and room temperature). This is reproduced in Figure 7. These experiments were carried out in tubes of different diameters (up to $30\,cm$) and orifice plates (at various spacing) were used as flow obstructions. It appears that for lean mixtures the maximum flame speed is below a $100\,m/s$, but around 12% H_2, the mixture is sufficiently sensitive to permit a transition to another regime (choking regime) where the flame speed is of the order of hundreds of meters/sec. In this so-called choking regime, transition to detonation can readily be achieved when the boundary conditions (the available scale for the propagation of the detonation) permit. In all cases, the corresponding laminar burning velocity is of the order of a few meters per second, thus the McGill results are two to three orders of magnitude larger than the factor of 10 assumed for the vent code calculations in the Darlington report. Corresponding measurements of flame speeds for H_2-air-steam mixtures under conditions appropriate to a LOCA in the Darlington reactor vault have not been carried out and it is certainly important to do so to assess the maximum flame speed attainable in a H_2-air-steam mixture under realistic conditions. At any rate, for high flame speeds (e.g. $\sim 100\,m/s$), the vent code is no longer applicable and more sophisticated codes taking into account shock waves must be used. Such codes are currently available and with the appropriate modelling

for the turbulent flame, quite acceptable results can be obtained. Examples of such codes are the Flux Corrected Transport (FCT) code developed by the Naval Research Laboratories, the CONCHAS-SPRAY and KIVA codes developed by the Los Alamos National Laboratories, and the Turbulent Transport code developed at the Christian Michelsen Institute (CMI).

2.2 Flame Acceleration

Regarding flame acceleration in larger scales, SANDIA at Albuquerque[5] has carried out experiments in various sized apparatus (e.g. FITS - a cylindrical tank 5.6 m^3 volume, 1.5 m diameter × 3.4 m tall, VGES - a 5 m^3 volume cylindrical tank, 1.22 m diameter and 4.27 m long, FLAME - a concrete rectangular channel 1.83 m × 2.44 × 30.48 m and MINIFLAME about a 5-fold scaled down version of FLAME). The schematic of VGES and FLAME are shown in Figures 8, 9 and 10. The results from these experiments of flame propagation in an obstacle field all indicate flame speeds in excess of the estimated 10 times the laminar flame value used in the Darlington report. However, it should be pointed out that tests with hot mixtures of H_2-air-steam of composition near the "assumed ignition limit" of the Tayco igniters have not been carried out. It is of importance to perform such experiments in an obstacle-filled heated tube to establish the maximum burning rate in mixtures under postulated accident scenarios in the Darlington reactor vault.

2.3 Transition to Detonation

The most severe loading on the structure is due to transition and detonation. It is of interest to first point out that in the large scale FLAME facility of SANDIA, transition to detonation has been observed in as lean as 15% H_2 (Figure 11). The channel is only about 30 m long and a typical cross-section dimension is 2.5 m giving a L/D ratio of about 12. The old view of detonation transition stated that hundreds of tube diameters are required. It should also be pointed out that the old view of the lean detonability limit is 18.2% and recent results indicate a lean limit of 11.7% H_2 at 20°C and for a higher initial temperature of 100°C, 9.5% H_2 has been detonated in 0.43 m diameter hot tube facility at SANDIA. Even with little confinement (e.g. 50% venting on the top wall of the FLAME channel), transition has been observed in mixtures of about 20% H_2 (Figure 11).

Of greater importance is the large scale experiments carried out in Norway[6] and Defense Research Establishment Suffield (DRES)[7]. Moen reported transition in an unconfined fuel-air mixture contained inside a plastic bag[6]. The implication of Moen's experiments is that hardly any flame acceleration is required when the conditions for large scale turbulent vortex mixing can be achieved. Although Moen used acetylene-air mixtures, the equivalent sensitivity of this mixture is about 19.35% hydrogen in air according to cell size scaling. More recent experiments at DRES[7] indicate that a flame jet emerging from a tube into an unconfined mixture can lead directly to transition. The typical flame jet velocity required is of the order of a few hundred meters per second and these jet velocities can readily be achieved if the combustion products of a confined explosion

were to be suddenly vented into an unconfined volume of combustible mixture. The recent jet initiation experiments at McGill[8] indicate that lean mixtures are in fact easy to detonate by turbulent mixture since the demand on the turbulent mixing rate is less severe. However, lean mixtures require a larger detonation kernel or mixing volume. Thus in proto-typical conditions of a large scale event, transition in a lean mixture due to mixing with product gases is not as highly improbable as once thought. Transition experiments in H_2-steam-air mixtures have also recently been carried out in a 5.4 m^3 heated vessel 11 m long and 0.8 m diameter at Battelle-Institut in Frankfurt[9]. The vessel is a concentric cylinder with an inner cylinder of 0.4 m diameter. The flame is initiated in the inner tube and after propagating the length of the tube, emerges into the outer annular region where transition is observed. Figure 12 shows a schematic of the Battelle facility. The region in the H_2-steam-air composition triangle in which transitions have been observed are given in Figures 13 and 14. The steam-H_2-air mixtures where transitions have been reported are certainly within the possible values assumed to exist in the pockets of Table I. For example, in case I, where the 230 *kmol* pocket consists of 152 *kmol* air, 64 *kmol* H_2 and 14 *kmol* steam (i.e. 66% air, 28% H_2, 6% steam), the mixture composition is within the shaded transition zone of the Battelle experiment shown in Figures 13 and 14. It may be concluded that the 10 times laminar burning velocity assumption used in the VENT CODE analysis and disregarding the possibility of transition and detonation in the Darlington report, are not compatible to the current state of the art from recent large scale experiments on the combustion behavior of hydrogen.

The final issue concerns the explosion of the hydrogen-rich pocket that always surrounds the release of a hydrogen rich jet. For high rate of H_2 release, the explosion of such a pocket often results in transition to detonation and severe blast damages. A number of industrial incidents are documented in Appendix C to substantiate this possibility. Recent large scale experiments have also been carried out by Battelle Institut in Frankfurt to investigate the explosion overpressure from such a pocket[10]. Propane is used and the release from an opening from 4 mm to 80 mm has been studied. Different types of situations have been investigated: i) release from 1.8 m height giving an unobstructed vapor cloud, ii) release from 0.6 m from the ground under different angles with respect to the ground, and iii) the jet impinges on an obstacle array with partial confinement. The maximum overpressure is found to scale with jet diameter. This has been credited to the turbulent scale in the cloud prior to ignition, which is proportional to the jet size. The presence of obstacles further increases the overpressure by a factor of three to four, giving a maximum overpressure of 0.2 *bar* for the 80 mm opening. Typical flame speeds range from about $30 m/sec$ to $100 m/sec$. The schematic of the experimental arrangement, the pressure-time profiles for different jet openings, the variation of the maximum overpressure with orifice diameter, and the relationship between the overpressure and the observed flame speeds are given in Figures 15, 16, 17 and 18, respectively. Such experiments using H_2 or a H_2-steam mixture have not been previously studied and should be of importance to gain some quantitative understanding of the possible consequences of the explosion of a H_2 rich jet in an oxidizing atmosphere. It should be noted that the Battelle experiments use propane, a much less sensitive mixture than hydrogen. Also, the maximum size of the jet release is only

80 mm. With the increase in both flame speed and overpressure with increasing jet diameter, it would be important to carry out experiments of a larger jet diameter for the case of H_2. It is also highly recommendable to carry out some blast calculations from the explosion of such a pocket. If the fast release of a hydrogen-rich mixture from a relatively large diameter opening into an oxidizing atmosphere cannot be ruled out, then a quantitative estimate of the explosion of such a pocket is essential to obtain an estimate of the pressure loading.

2.4 Standing Flames

The question of standing flames was not addressed in the DSR. It has been confirmed experimentally that upon ignition, a flame can flash back to the source of the H_2 release. If the H_2 concentration in the discharge jet is sufficiently high and the environment contains sufficient oxygen, then a standing diffusion flame can be established. The flame is anchored at the orifice (or break) for a low velocity discharge or at flow obstacles some distance from the discharge itself. The consequence of a standing flame is "torching" where very high heat fluxes are imparted to equipment where the flame jet impinges upon. The large scale EPRI-NTS studies in a 2100 m^3 spherical vessel have confirmed the possibility of standing flames. Serious considerations must be given to the prevention of standing flames near important equipment which may adversely influence the management of the accident.

2.5 Summary Remarks Regarding Combustion

In summary, the comments on the combustion analysis of DSR are itemized below.

1. The Tayco igniters operate when the mixture approaches the "assured ignition curve" from outside the flammability limits. Thus ignition occurs when the mixture is just within the flammability limit. The flame of near limit mixtures can easily be quenched by turbulence. Thus the combustion wave may not propagate away from the igniters to consume the hydrogen in the vault volume as expected.

2. The VENT CODE is based on a one-dimensional geometry. Even for slow flames, venting can result in the excitation of acoustic instability leading to large pressure fluctuations.

3. The most conservative situation selected for a spherical geometry with central ignition for the reference case is not the most conservative. If multiple ignition sources are used (as in the present case where a number of Tayco igniters are energized simultaneously), the pressure rise should be proportional to the number of developing flame kernels. Thus, the rate of overpressure development may be much higher than that from a single ignition source.

4. The sensitivity analysis using a 3% gradient to account for non-uniformity in the mixture composition inside the vault volume only implies a mixture 3% richer in H_2 than that defined by the "assured ignition curve" of the Tayco igniters. It still assumes

the mixture inside the vault volume to be uniform, hence perfect mixing.

5. Regarding the sensitivity analysis where a pocket of stoichiometric H_2-air mixture is obtained, there is no reason to assume that steam is present in the pocket since one permits the non-uniformity to occur due to poor mixing. The situation where the steam condenses out and air is drawn in to replace the condensed steam volume mixing with just the hydrogen to form a pocket of stoichiometric H_2-air mixture (without any steam), is perhaps more likely since there is one less component to mix. In this case a more detonable pocket would be present.

6. Even if the mixture in the pocket is assumed to be that given in Table F9-4 of the Darlington report, the VENT CODE calculations are carried out using a less conservative case of side ignition (instead of central) and burnt gas venting (instead of unburnt gas venting). The change in conditions used should be justified since the Tayco igniters are presumably energized and central ignition and unburnt gas venting as in the reference case should be equally likely if not more so than a spurious ignition source near the vault floor. Furthermore, the multiple ignition source from the igniters should be used in the VENT CODE calculations rather than the single igniter assumption.

7. The 10 times laminar burning velocity assumption for the flame speed in the VENT CODE calculation is not justifiable from the experiments at McGill, SANDIA, DRES, and Battelle which indicate the possibility of one or two orders of magnitude higher flame speeds. Transition to detonation cannot be ruled out.

8. Transition to detonation has been observed in as lean as 15% H_2 in the FLAME-facility of SANDIA and for H_2-air-steam mixture, the Battelle experiments have indicated transition to occur in mixtures within the estimate of those in the pockets when steam condenses out and air is drawn in to replace the volume.

9. Recent large scale experiments by Moen, by Ungut at Shell Thornton Research Center[11], and McGill, all confirm the possibility of transition by jet mixing of combustion products with unburnt mixture. This implies that transition does not require flame acceleration, confinement and a long flame travel as concluded from classical experiments. Furthermore, the recent McGill results indicate that weaker mixtures are less demanding than more sensitive mixtures in terms of the turbulent mixing rate for transition. However, the scale of the mixing zone should be increased according to the cell size.

10. Battelle has also carried out experiments of the explosion of the combustible gas volume surrounding the jet release of propane. It is found that the maximum overpressure and flame speeds scale with the opening of the jet release. As high as 0.2 *bar* has been observed even for propane from a 80 *mm* diameter jet. If the scaling law applies, extrapolation to a diameter an order of magnitude larger would lead to unacceptable overpressures. Furthermore for hydrogen, much higher flame speed and maximum overpressure would be obtained than for propane. Industrial accidents confirm the violent explosions of H_2 releases.

11. The issue of standing flames must be considered and efforts must be made to locate and prevent the occurrence of standing flames near critical equipment.

D. ASSESSMENT OF POSSIBLE HYDROGEN RELEASE SCENARIOS AND MIXING IN THE DARLINGTON REACTOR VAULT

In this section we address the request to put forward a list of possible scenarios for the distribution of hydrogen in the vault as a function of the hydrogen and hydrogen-steam discharge rates. We therefore postulate the following discharge scenarios with an assessment of the concomitant hydrogen distribution in the reactor vault.

1. High Speed Jet Discharge (High subsonic or choked jet) - Fans-on, Fans-off

(a) If the discharge is in the form of a high speed jet and the discharge medium is hydrogen-steam with a high steam proportion (steam-hydrogen ratio 2.5:1 or greater) then nowhere in the vault will one have detonable proportions (even a stoichiometric H_2-air mixture would be 40% diluted with steam). Fully mixed conditions would essentially be completed in the mixing zone of the jet ($x/d \geq 200$) and the fully mixed vault hydrogen-steam concentration would gradually rise as the discharge continued. The role of fans would have a very minimal effect on the mixing scenario.

(b) If the discharge is in a high speed jet and the discharge medium is predominantly hydrogen (due to blow-down conditions or steam condensation before discharge), then a detonable footprint will definitely be formed in the near field of the jet. An example of the scale of the footprint is illustrated in Appendix B for a postulated 5 *cm dia* rupture. The turbulent mixing zones and length scaling are well known and easily calculable from turbulent jet theory. The important conclusion for this scenario is that an explosive footprint will always be formed in the near field of the jet mixing zone. Again the role of fans would have a negligible effect on the momentum dominated mixing in the jet.

2. Buoyant Plume Discharge (Low Froude Number) - Fans-off

(a) If the discharge is in the form of a low Froude number buoyant plume and the discharge medium is hydrogen-steam, then the plume will rise by buoyancy with the possibility of the steam condensing out. There is the very likely possibility of stratification of hydrogen at the top of the reactor vault.

(b) If the discharge medium is pure hydrogen, then it will rise in the plume and stratify at the top of the reactor vault. The thickness of the stratified layer will depend on the duration of the efflux. A gradient of concentration of hydrogen will characterize the thickness of the cloud with the leanest hydrogen-air concentration being near the bottom of the layer and the richest at the upper wall.

3. Buoyant Plume Discharge (Low Froude Number) - Fans-on

Whether the discharge medium is hydrogen-steam or pure hydrogen, condensation of the steam will most likely segregate the hydrogen for a hydrogen-steam discharge anyway. The fans-on situation will tend to alter the tendency to stratify the hydrogen. However, although the fans have a high capacity, the flow they induce is directional. Thus although they can process in time the contents of the vault several times over, pockets of stagnant recirculating flow can be formed behind obstructions and in corners. It is well known that mixing in such recirculating zones is minimal because it is essentially diffusion dominated. Accumulation of hydrogen in such pockets is conceivable.

E. RECOMMENDATIONS

1. Mixing

It is higly recommended that "in situ" mixing tests be carried out in the Darlington reactor vault. It is also recommended that computer simulation of the hydrogen dispersion processes as well as the pressure transients associated with intentional ignition using one of the numerous existing codes developed for this purpose be carried out. The justification for the recommendation of the "in situ" tests are given below:

1.1 The basic premise of the Darlington Safety Report that any hydrogen burn is within the safe structural limits of the containment is essentially predicated on the validity and applicability of the HEDL test to the Darlington situation. Our view is that this is not so. The HEDL tests were structured to simulate the lower containment of an ice condenser plant. In order to scale the results one needs to have geometric similarity as well as dimensionless fluid mechanical scaling of the dispersion process.

(a) There is no geometric similarity between the HEDL tests (cylindrical baffled chamber) and the Darlington reactor vault (rectangular room with blockages).

(b) The HEDL tests were run only in the high Froude number mode (intense jet) with high steam content. The high concentration gradient in the mixing footprint of the jet was not addressed nor instrumented for measurements. If, in the Darlington vault the possibility of a pure hydrogen release is admitted in a high speed jet, this would definitely lead to an explosive footprint which would scale according to the rupture dimension.

(c) The HEDL tests did not simulate the buoyant low Froude number release. If in the Darlington vault such a release is a possibility then this will lead to stratification of a hydrogen layer in the upper reaches of the reactor vault if the fans are off. With fans on, the possibility exists of pockets of stagnant recirculating flow, which are hydrogen rich, accumulating in corners and behind obstacles which can develop due to the directionality of circulation induced by the fans.

1.2 With regard to the high Froude number discharge in a high speed jet, the details of the mixing flow field can readily be established analytically from jet mixing theory. Since the bulk of the mixing will occur in the near field of the jet (as indeed the HEDL tests have indicated), the global hydrogen concentration will progressively increase in time in the rest of the vault as the discharge continues. The medium will be in the essentially fully mixed condition.

For low Froude number releases it is essential to establish the stratification and dispersion pattern in the specific Darlington reactor vault with fans-off and fans-on. Only in this way can a meaningful distribution of igniters be established and located in the appropriate spots. For fans-off, this would predominantly be in the upper portion of the reactor vault. For fans-on it would be in the identified recirculation pockets set up by the directional flow induced by the fans.

2. Combustion Analysis

1. It is recommended that the VENT CODE be used to estimate the consequences of multiple ignition sources (compatible to the number of Tayco igniters used in Darlington). Irrespective of the validity of the assumption used, such a reference calculation should at least reflect the actual situation of ignition inside the vault.

2. A more realistic computation should be carried out using a blast code capable of handling pressure waves. This calculation should address the volumetric explosion (or detonation) non-uniform pockets inside the vault. The pocket may be due to poor mixing, stratification or release from a H_2 rich break in the system.

3. In view of the fact that the maximum turbulent flame speed for hot steam-air-hydrogen mixtures has not been measured, it is recommended to carry out such experiments to provide a reference basis on the most conservative values for the turbulent burning rate of mixture, particularly near the assured ignition limit of the Tayco igniters.

4. Emphasis should be placed on further studies of the transition phenomenon to establish the criterion of its occurrence. Currently, the influence of initial and boundary conditions on the flame propagation at the onset of transition to detonation is not known. Small, university-level, laboratory scale experiments should be instituted to achieve a systematic assessment of such influences. These experiments should then be followed up at WNRE on a larger scale to determine the effects of scaling on the transition phenomenon.

5. Similar studies as those of Battelle of the ignition of steam-H_2-air mixtures from a jet should be carried out. These large scale experiments are best carried out at WNRE.

F. CONCLUSIONS

Detailed analysis of the DSR indicates that both of the key assumptions (i.e. uniform mixing and a burning rate corresponding to 10 times the laminar burning velocity) cannot be justified. If the mixture cannot be assumed to be uniform, the appropriate choice for the locations of the igniters must be carefully examined. In situ mixing experiments carried out at the Darlington reactor vault prior to the reactor being commissioned should yield valuable information on hydrogen distribution. If furthermore, one of the currently available computer codes (e.g. HECTR, RALOC, MARCH, etc.) is used to model the Darlington vault then the data from the "in situ" tests can be used effectively to calibrate the code. The assumption of 10 times the laminar burning velocity is not compatible to existing state of knowledge of hydrogen combustion. Accelerated flames and transition to detonation are possibilities that have to be addressed. No realistic flame acceleration or transition to detonation studies, that would be relevant to the scale inherent in the Darlington reactor vault, have been carried out by WNRE. A number of the outstanding areas of knowledge in large scale H_2 flames should be investigated at WNRE under a carefully planned program. Coordination with EPRI and USNRC supported programs and DOE laboratories currently engaged in the H_2 problem should be made.

In a more general sense, irrespective of what mitigation scheme is used, the threat to containment integrity due to hydrogen combustion cannot be avoided entirely if large amounts of hydrogen are released rapidly into an oxidising atmosphere. For better management of accidents and minimizing the adverse effects of hydrogen combustion the current state of the art in the understanding of the phenomena associated with large scale hydrogen combustion must be advanced. There are a number of key scientific issues that must be resolved (eg. the transition criterion from flame to detonation, scaling of turbulent flames, large scale diffusion jet flames, etc.). It is important that the utilities acknowledge the existence of such problems and that the regulating agencies recognize that effective measures for the prevention, mitigation and suppression of hydrogen explosions require a long term research effort. It is recommended that both the utilities and government agencies make such a long term commitment to the eventual resolution of the problem by maintaining active support of scientific research in the field in both government research organizations and the universities. It also is highly recommended to improve communication among the various interest groups (eg. COG, AECL, AECB and the universities) by holding annual meetings to coordinate the research effort. The safety of nuclear plants is a long term requirement and the expertise in the country in this direction must be nurtured.

TABLE I

ANALYTIC ASSUMPTIONS USED FOR COMBUSTION ANALYSIS

1. Initial conditions : 333 K. 80 kPa
2. Vault atmospheres are well mixed with hydrogen concentration gradients not exceeding 3% .
3. Vault is modelled as a spherical combustion vessel of volume 13671 m3 .
4. Unburnt gas is vented through a vent size 183.6 m2
5. Effective flame speed is 10 times laminar burning velocity.

TABLE II

FLAMMABLE POCKET SIZES & COMPOSITIONS ANALYZED

Vault Gas Inventory (80 kPa, 383 K) - 331 kmol

Vault Hydrogen Inventory - 148 kmol

BULK STEAM		POCKET COMPOSITION				POCKET TOTAL	POCKET SIZE
		AIR	OXYGEN	HYDROGEN	STEAM		
X	kmol	kmol	kmol	kmol	kmol	kmol	X VAULT VOL.
10	33	182	(32)	64	14	230	69.5
20	66	119	(25)	60	23	182	55.0
30	99	85	(18)	38	24	148	44.1
40	132	53	(11)	22	20	85	25.7
50	166	19	(4)	8	9	36	10.9

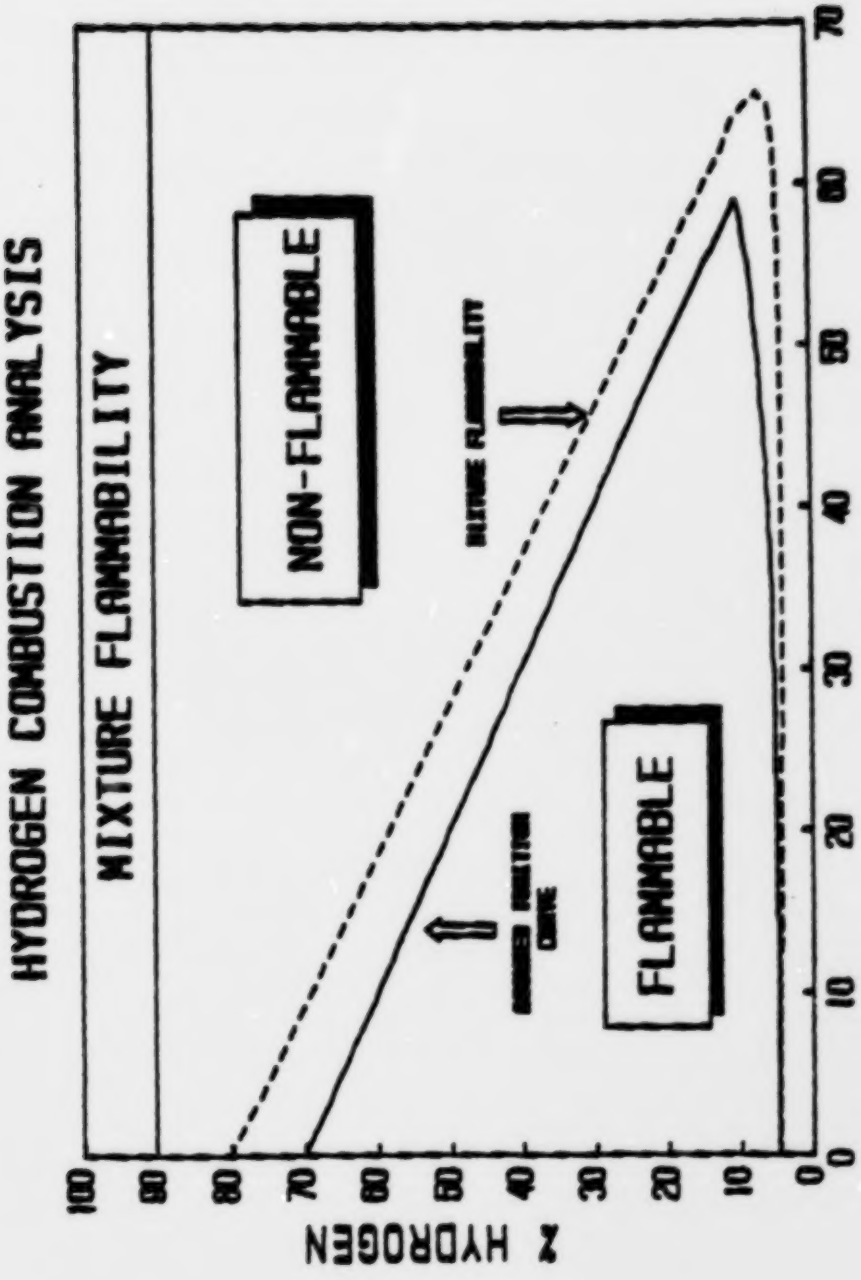

HYDROGEN COMBUSTION ANALYSIS
MIXTURE FLAMMABILITY
NON-FLAMMABLE
FLAMMABLE
% HYDROGEN
Z STEAM
0
10
20
30
40
50
60
70
80
90
100

Figure 1

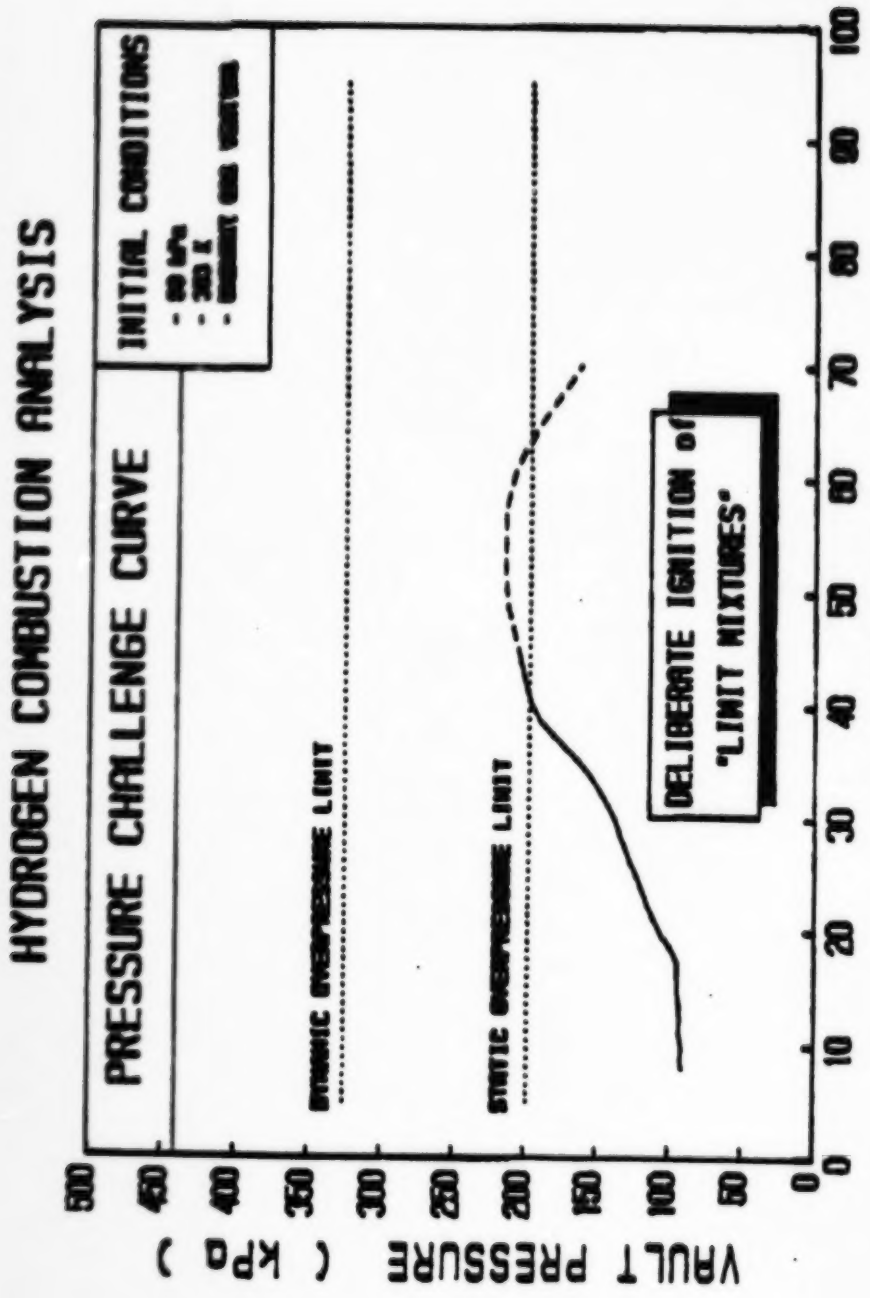

HYDROGEN COMBUSTION ANALYSIS
PRESSURE CHALLENGE CURVE
INITIAL CONDITIONS
DYNAMIC OVERPRESSURE LIMIT
STATIC OVERPRESSURE LIMIT
DELIBERATE IGNITION of "LIMIT MIXTURES"
VAULT PRESSURE (KPa)
Z HYDROGEN
0
50
100
150
200
250
300
350
400
450
500
0
10
20
30
40
50
60
70
80
90
100

Figure 2

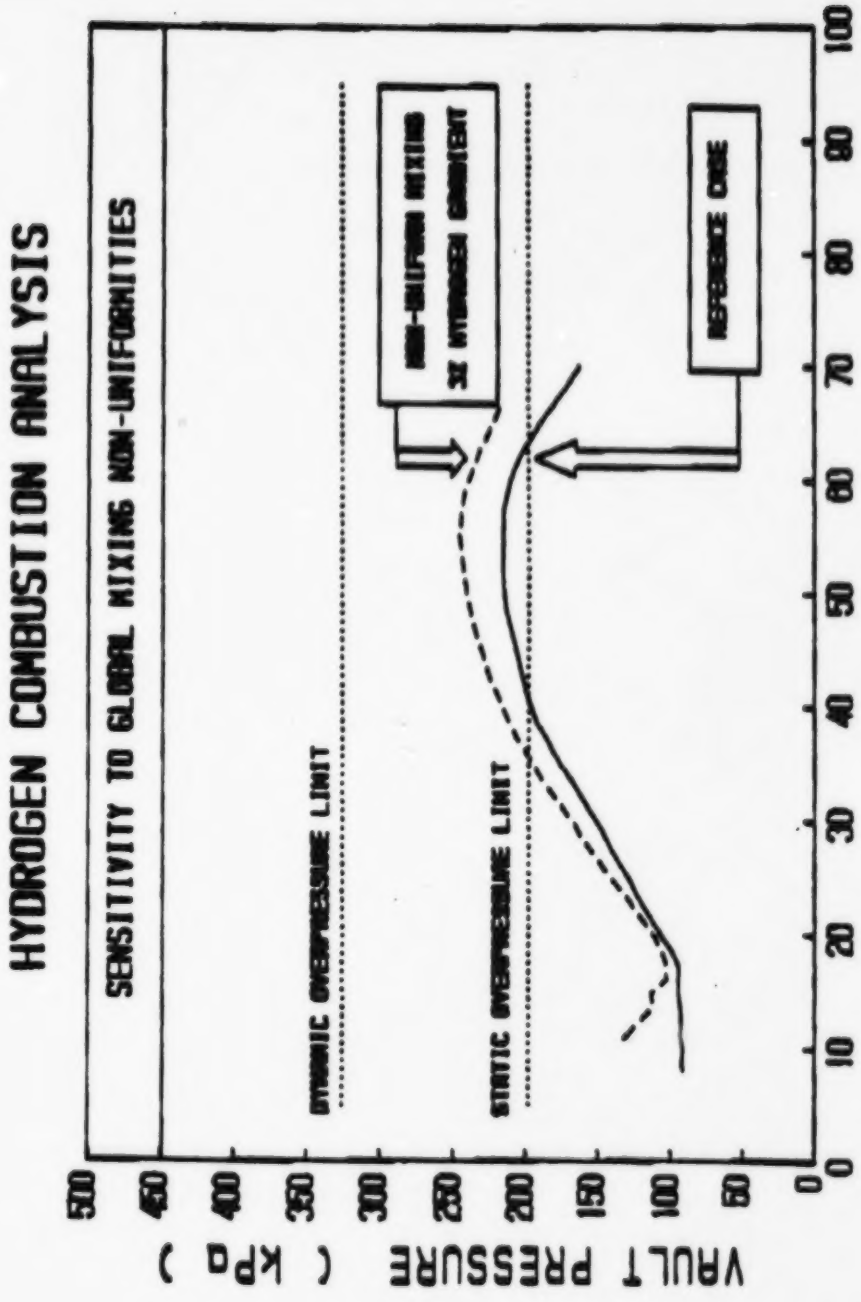

HYDROGEN COMBUSTION ANALYSIS
SENSITIVITY TO GLOBAL MIXING NON-UNIFORMITIES
DYNAMIC OVERPRESSURE LIMIT
STATIC OVERPRESSURE LIMIT
NON-UNIFORM MIXING
3% HYDROGEN CONTENT
REFERENCE CASE
VAULT PRESSURE (KPa)
500
450
400
350
300
250
200
150
100
50
0
0
10
20
30
40
50
60
70
80
90
100
Z HYDROGEN

Figure 3

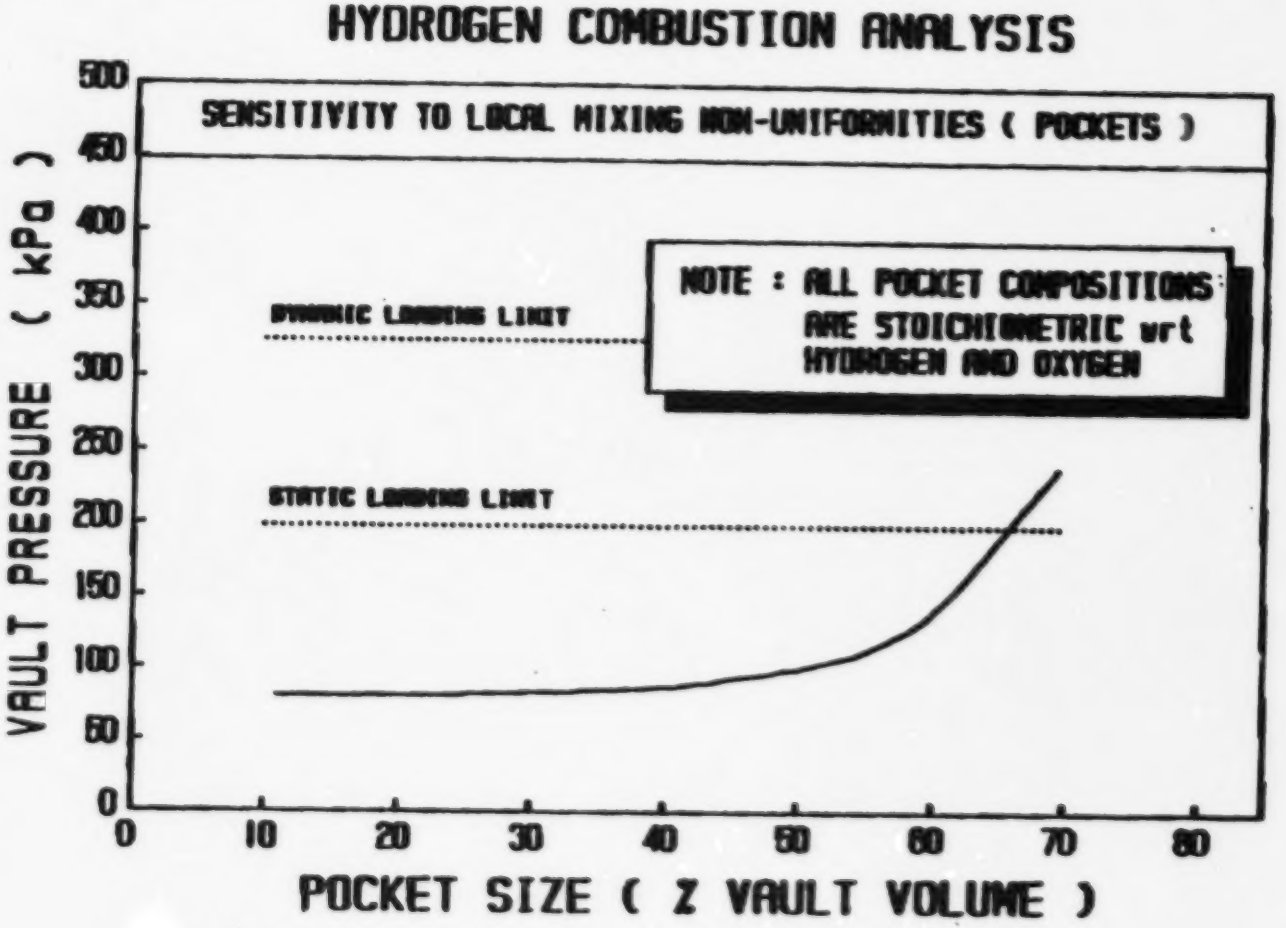

HYDROGEN COMBUSTION ANALYSIS
SENSITIVITY TO LOCAL MIXING NON-UNIFORMITIES (POCKETS)
NOTE : ALL POCKET COMPOSITIONS ARE STOICHIOMETRIC wrt HYDROGEN AND OXYGEN
STATIC LOADING LIMIT
VAULT PRESSURE (kPa)
0
50
100
150
200
250
300
350
400
450
500
0
10
20
30
40
50
60
70
80
POCKET SIZE (Z VAULT VOLUME)

Figure 4

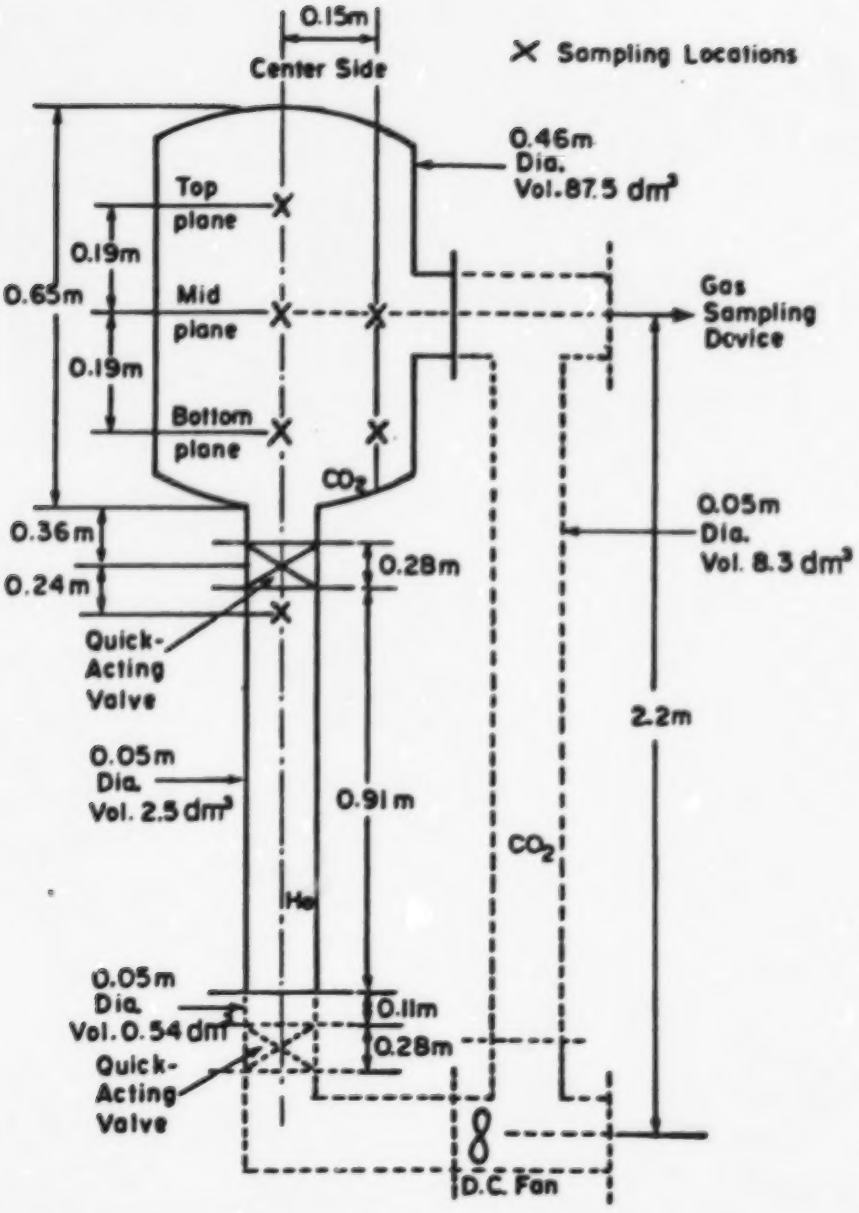


FIGURE 5 A Schematic Diagram of the Vessel-Pipe Assembly

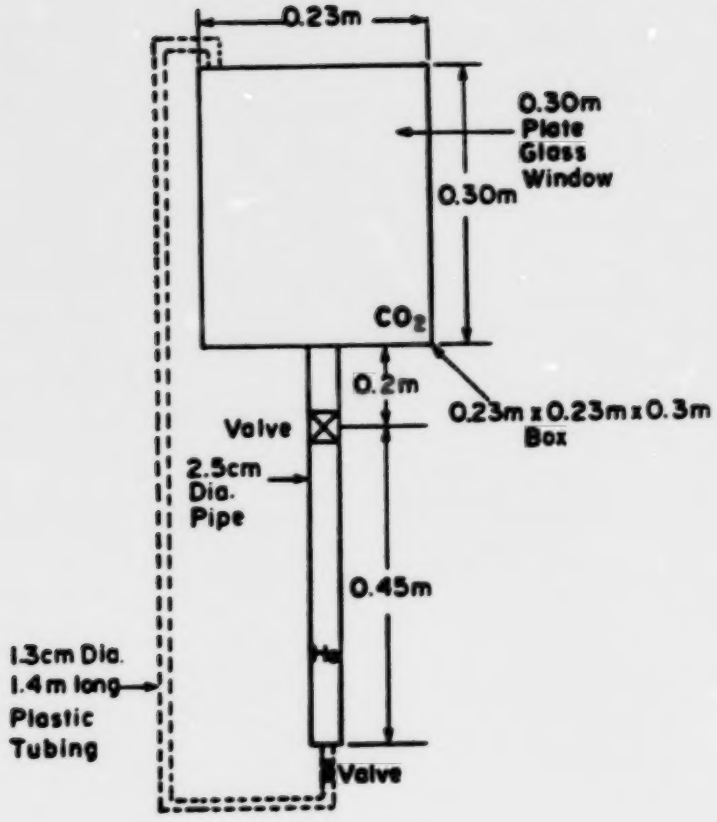


FIGURE 6 A Schematic Diagram of the Scaled-Down Vessel-Pipe Apparatus for Flow Visualization Tests

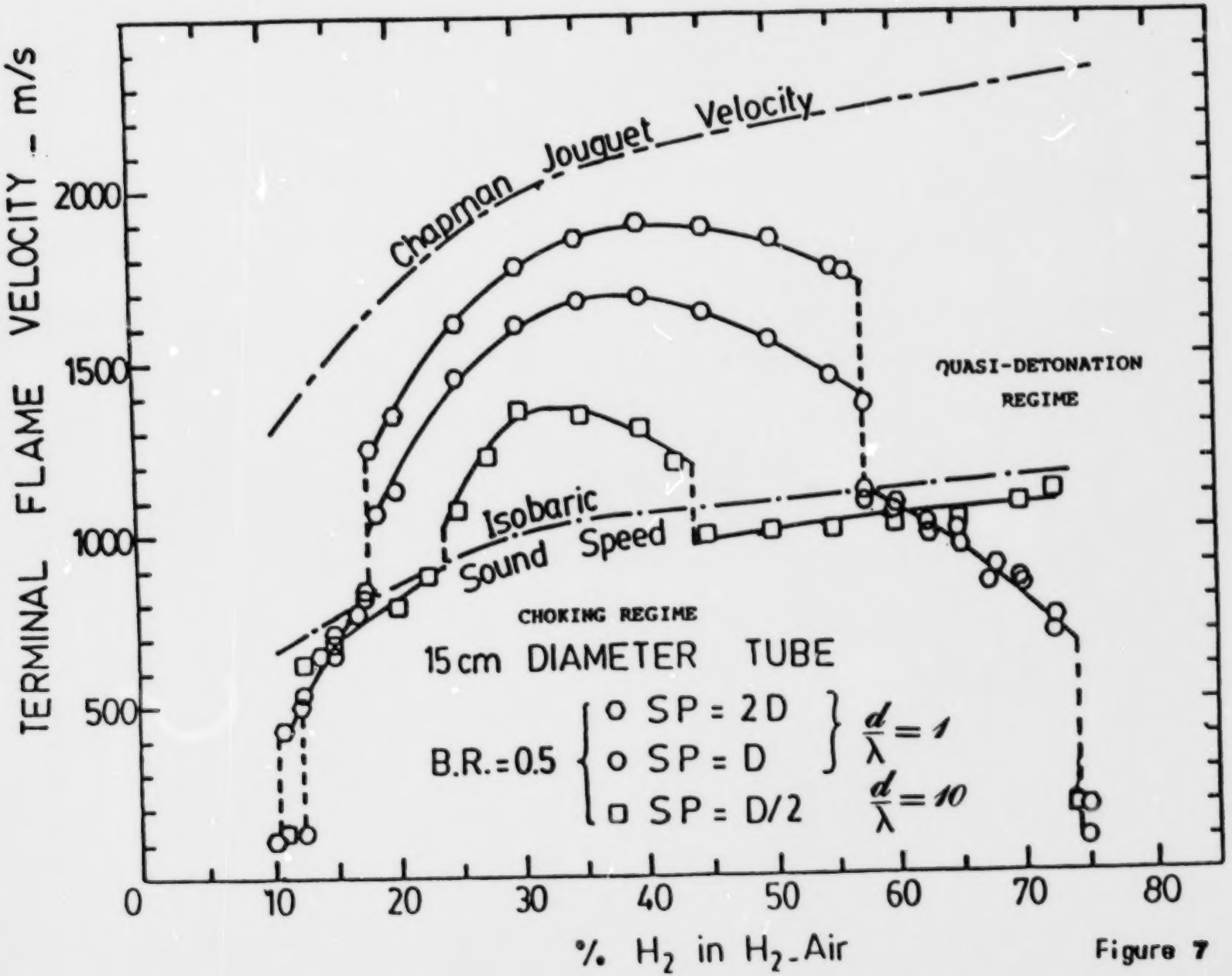
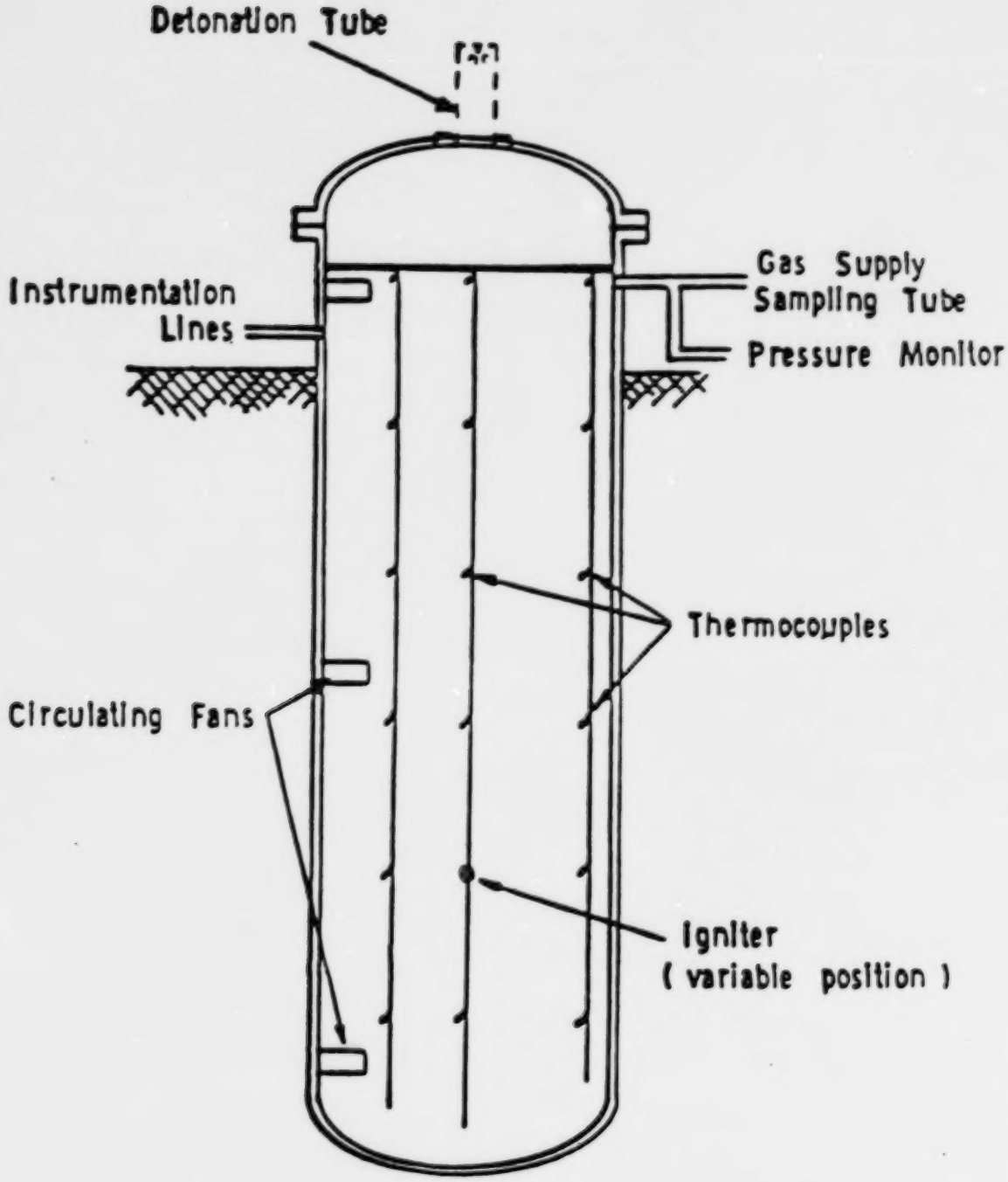

TERMINAL FLAME VELOCITY - m/s
2000
1500
1000
500
0
10
20
30
40
50
60
70
80
% H_2 in H_2-Air
Chapman Jouguet Velocity
QUASI-DETONATION REGIME
Isobaric Sound Speed
CHOKING REGIME
15 cm DIAMETER TUBE
B.R.=0.5
o SP = 2D
o SP = D
□ SP = D/2
$\frac{d}{\lambda} = 1$
$\frac{d}{\lambda} = 10$

Figure 7

VGES : 16 (14) - FT TANK



1.22 m (4 ft) diameter 4.27 m (14 ft) tall

5.0 m^3 (175 ft^3) volume

Figure 8

FLAME

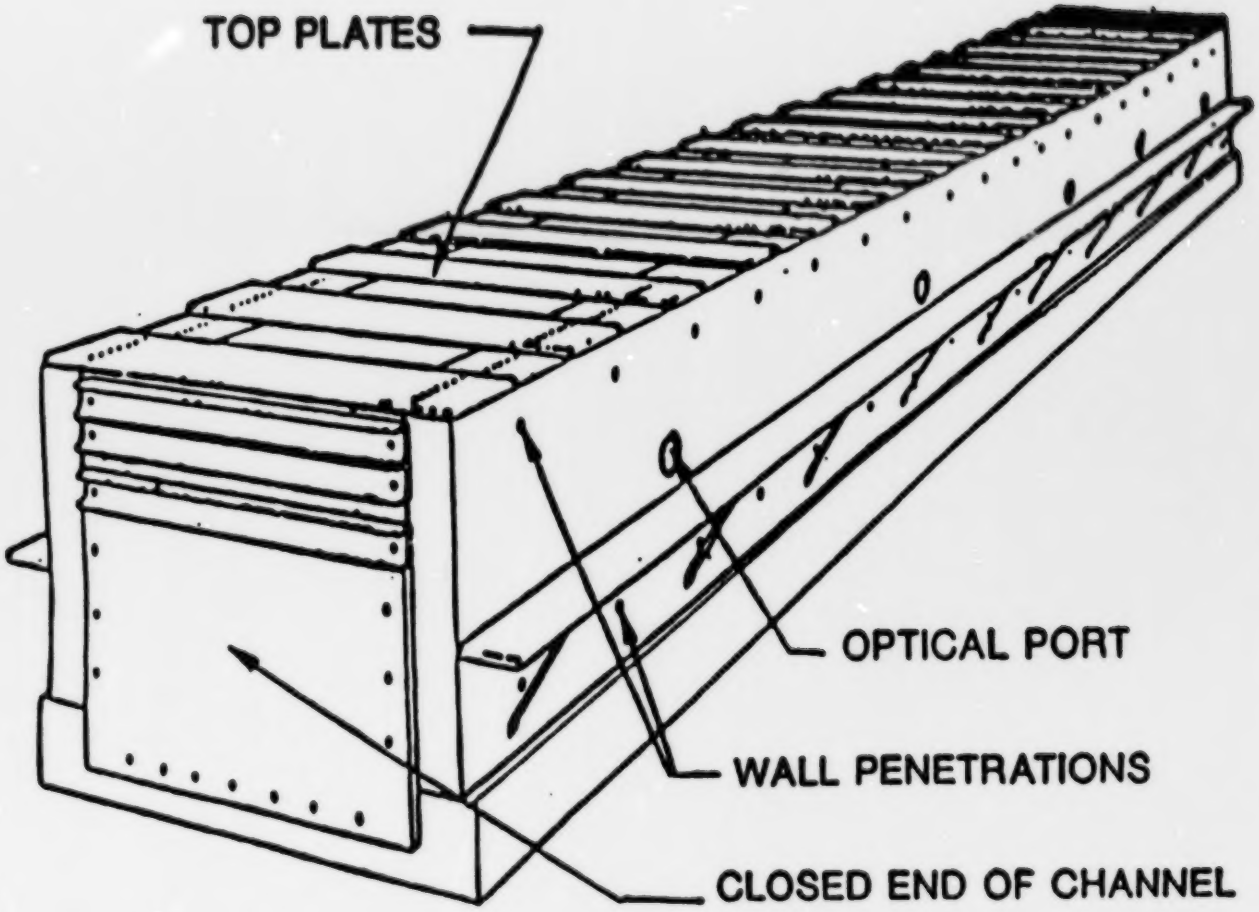


Figure 9

SCHEMATIC OF FLAME FACILITY WITH SIMPLE OBSTACLES INSTALLED, 33% BLOCKAGE RATIO

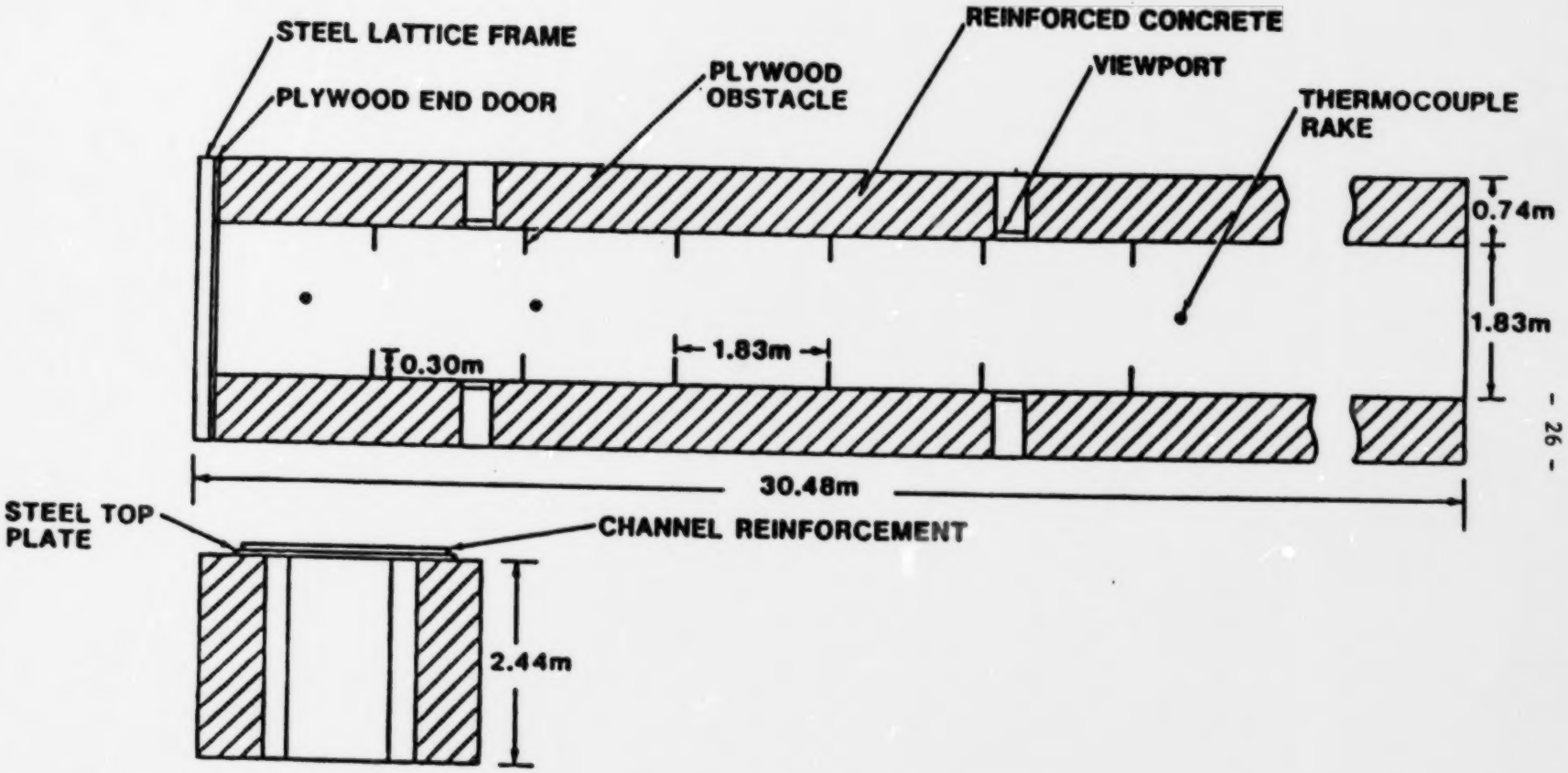


Figure 10

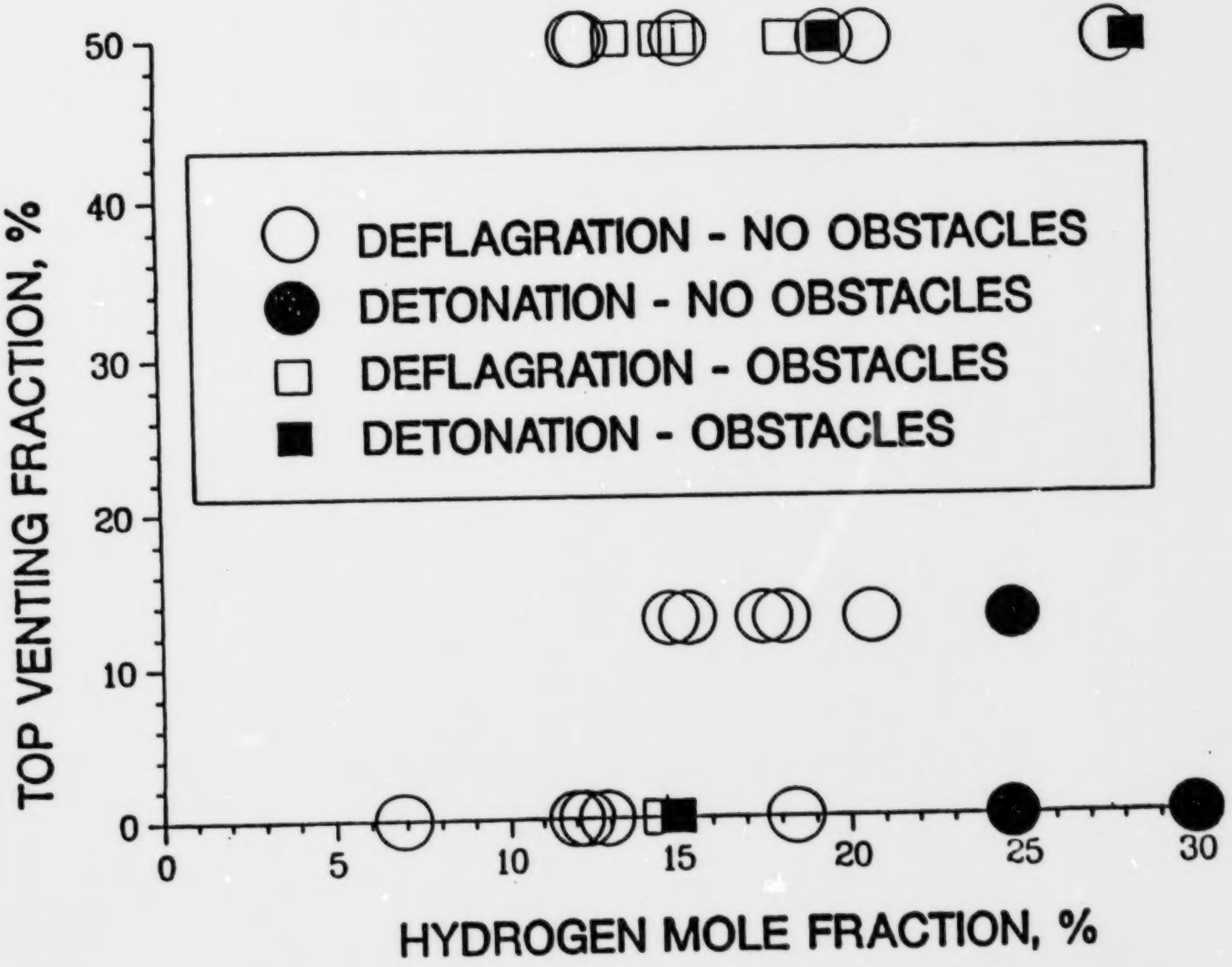


Figure 11

FLAME DDT Results

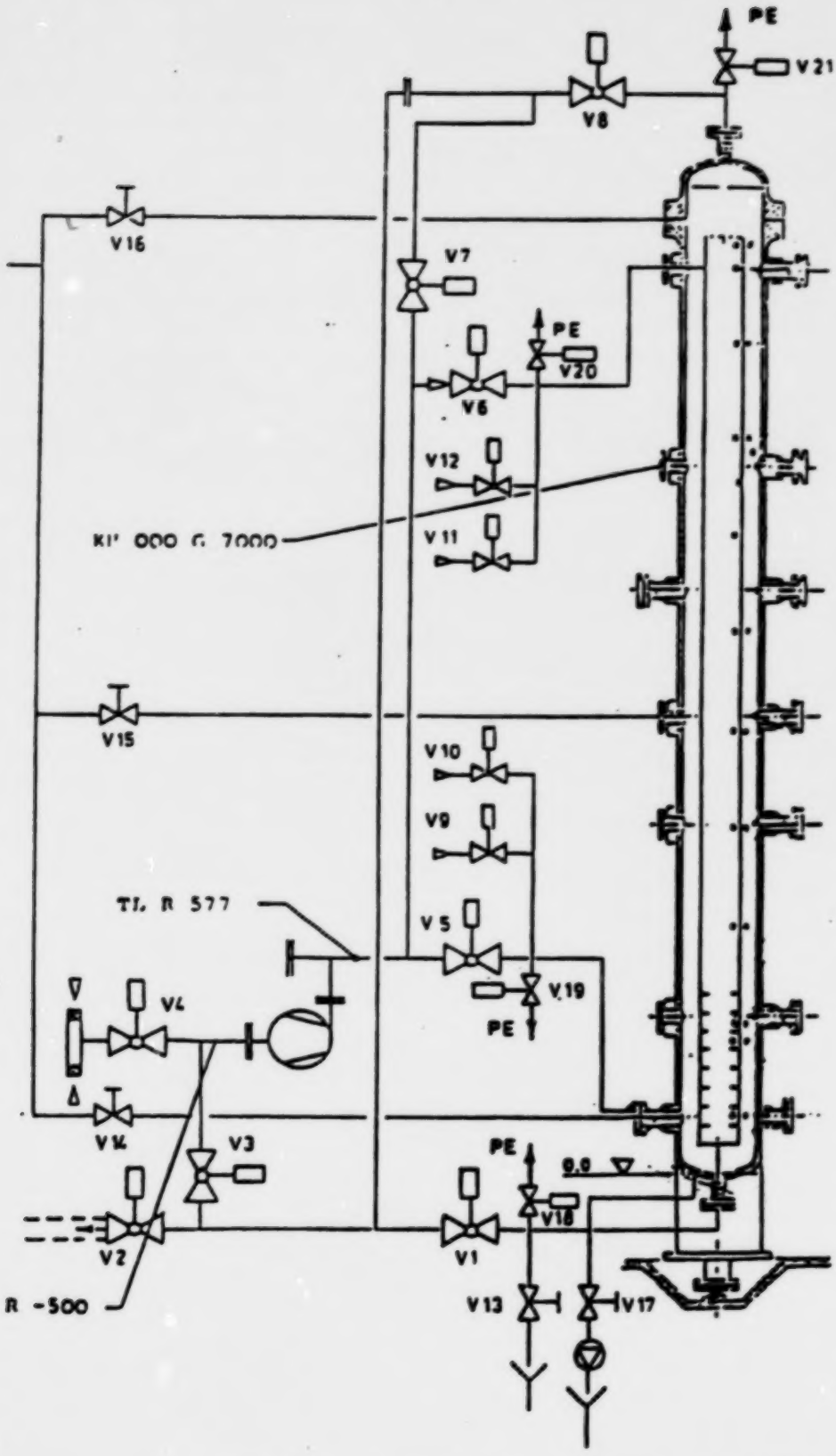


Figure 12 Test Facility at Battelle for DDT-Experiments

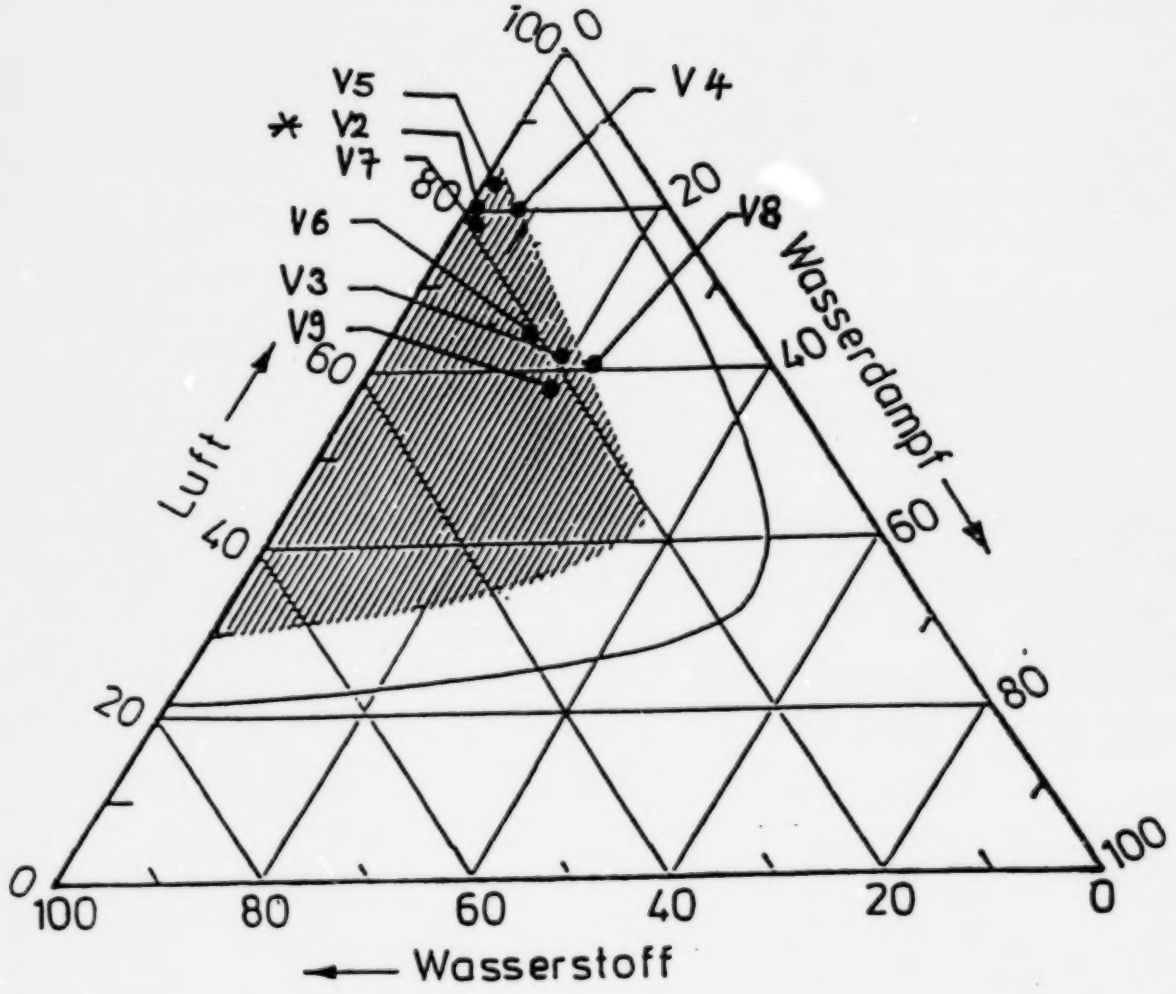


Figure 13 Gas composition of DDT-experiments - series 1

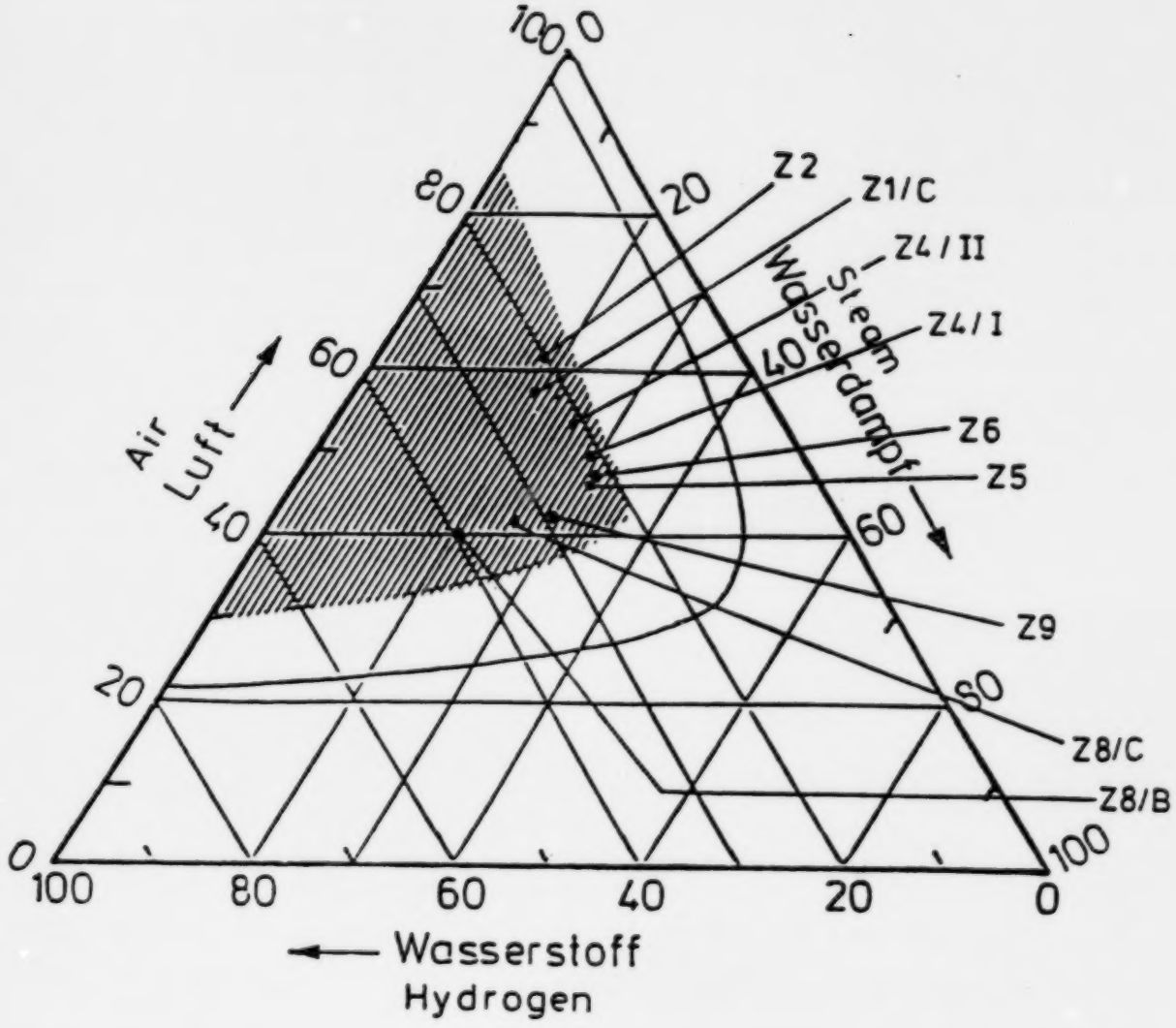


Figure 14 Gas composition of DDT-experiments - series 2

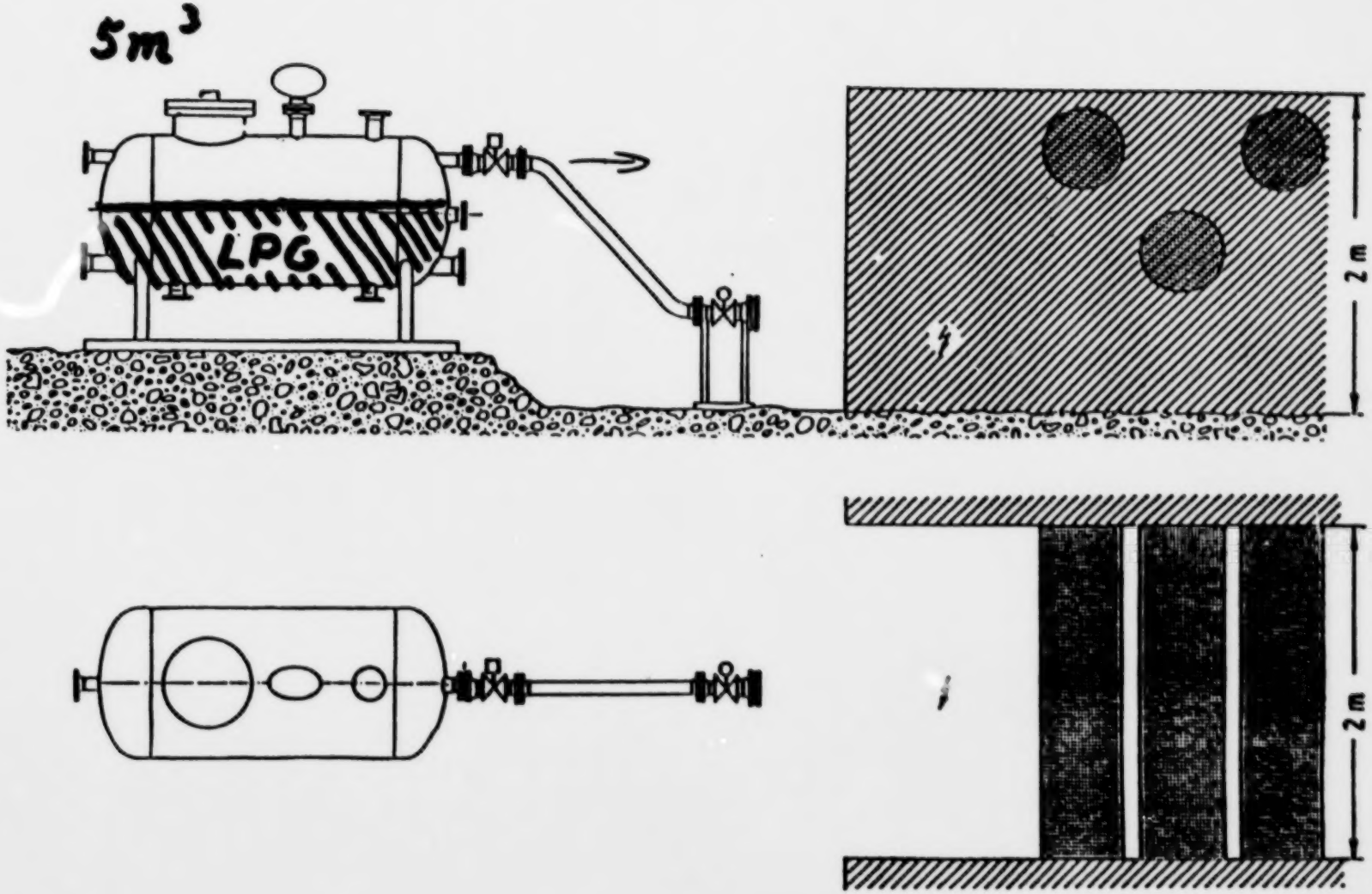


Figure 15

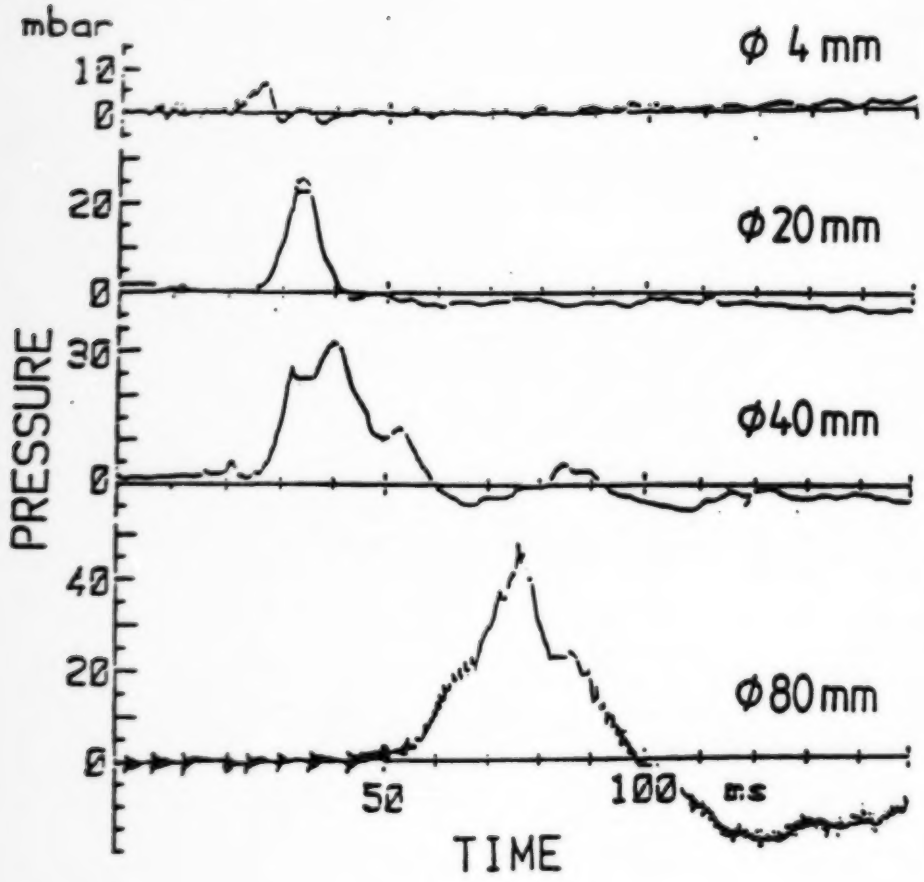

mbar
10
0
Φ 4 mm
20
0
Φ20 mm
30
0
Φ40 mm
40
20
0
Φ80 mm
PRESSURE
50
100
ms
TIME

Figure 16

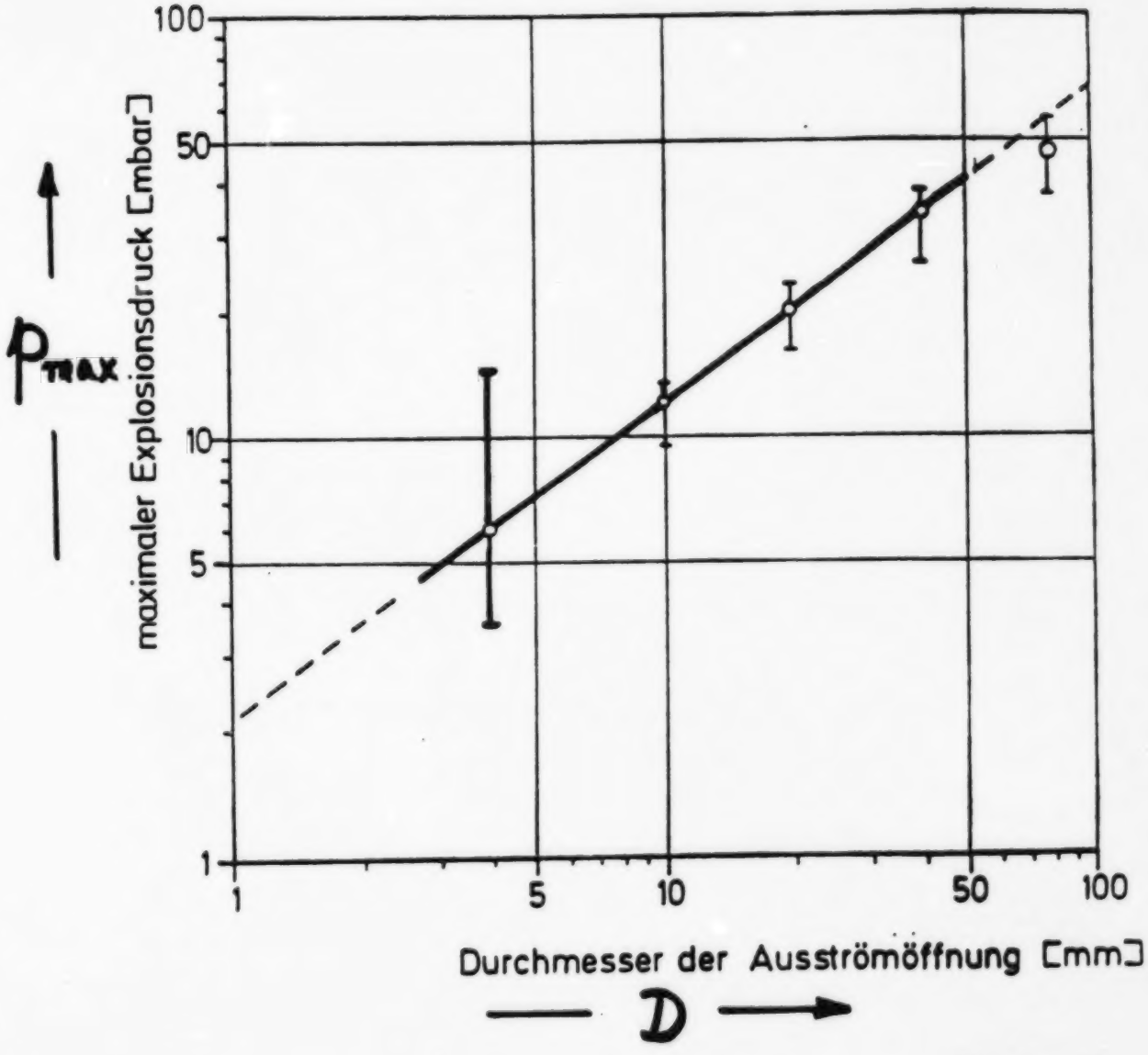

100
50
10
5
1
1
5
10
50
100
maximaler Explosionsdruck [mbar]
p_{max}
Durchmesser der Ausströmöffnung [mm]
D

Figure 17

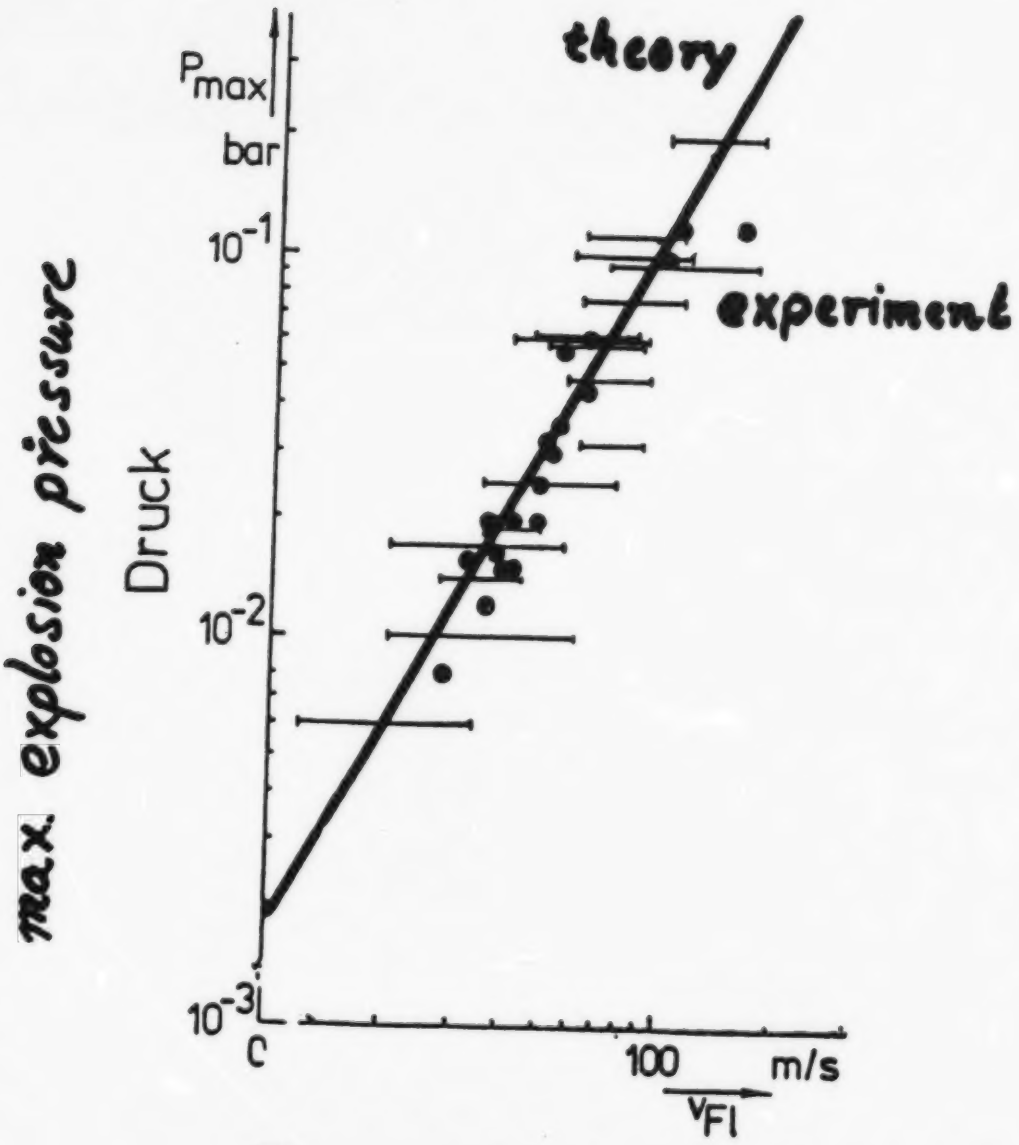

max. explosion pressure
Druck
P_{max}
bar
10^{-1}
10^{-2}
10^{-3}
0
100
m/s
v_{Fl}
theory
experiment
Flammenfrontgeschwindigkeit
flame velocity

Figure 18

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HYDROGEN MIXING AND COMBUSTION IN THE DARLINGTON REACTOR VAULT

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This report provides information in support of the previous report of March 28, 1988 and addresses the concerns expressed in the AECB letter of April 6 to Prof. Lee. There are three issues: how to interpret the HEDL test data and its possible application to the Darlington reactor vault; the general problem of modeling and scaling test information on hydrogen mixing; the justification and plans for additional testing on mixing.

1. HEDL Test Data

The issues in using the HEDL data to assess the hydrogen transport and mixing in the Darlington reactor vault containment are:

- Similarity between HEDL and Darlington reactor vault
- Scaling concentration fields
- Completeness of HEDL testing

Each of these issues is discussed below:

1.1 Similarity

As outlined in the report on the HEDL tests[1] and in textbooks on chemical[2] and mechanical engineering, similarity in geometry and flow parameters is required to in order to use the results of scale–model tests to predict full-scale performance. The HEDL tests were very specifically designed to model a portion (the lower compartment) of an Ice Condenser plant built in the USA. This facility and the tests done in it fail to model the reactor vault of the Darlington plant in three specific ways:

1.1.1 Geometry

The vault is a rectangular container with an interior excluded rectangular region (containing the reactor vessel) and is wider than it is tall (3:1 width:height). There are four coolers (each with two fans) located in the corners of the vault at about mid-height. The air in the vault is sucked at the cooler position and ducted to various locations. The vault contains a large amount of piping and other equipment which clutters up the volume. No source locations are proposed in the Darlington Safety Report (DSR).

The HEDL tests were carried out inside a large cylinder divided into two compartments: an upper cylinder and a lower annular region. The combined vessel had a diameter:height ratio of 1:2.5. There were slots connecting the upper vessel and the annulus and four blowers that drew air from the upper vessel into the annulus. There were two sources used, both were located near the bottom of the annulus. The cylinder and annulus were open, uncluttered volumes but the flow path between them was constricted.

The volume shapes, aspect ratio, and location of the fans are all differ between the HEDL facility and the Darlington reactor vault. The most important differences are in the aspect ratio and the presence of the constricted flow path between the upper and lower portions of the HEDL vessel. These changes are known to have a large effect in other problems involving mixing due to mixed natural and forced convection.

1.1.2. Flow parameters

The tests at HEDL were run at a specific jet condition: a 5 *cm* diameter jet oriented either horizontally or vertically. The flow rate was chosen so that the Froude number was between 100 and 200; this resulted in a nominal mass flow rate of 12.5 kg/min of steam and 0.4 kg/min of helium (see Appendix E of Ref. 1, the quoted values are for test HM-6, Figure E-6). A fixed concentration of helium (about 12.5%) was used in the helium-steam jet used to simulate the hydrogen-steam source. The recirculation flow rate used at HEDL was chosen to simulate the air return fans in an Ice Condenser plant and move air across the main obstruction to natural convection.

There are no data presented in the DSR that the HEDL source conditions and the air return flowrates can be taken as comparable to what might occur in an accident in a Darlington power plant. Most important, at HEDL, no tests were done with plume-like sources (Froude numbers less than one), a large open area above the source and no recirculation from top to bottom. This situation could occur at Darlington if the coolers were inoperative or ineffective at preventing stratification.

A test similar to that described above was performed in the NTS dewar tests[3] sponsored by EPRI and NRC. These tests resulted in a strong stratification being set up and very large (12%) differences in hydrogen concentration between the top and bottom (beneath the source) of the vessel.

1.1.3 Source

Both the Froude number of the source and the location were only slightly varied during the HEDL tests. Both parameters can have a strong effect on mixing efficiency. The use of jet sources and the location near the bottom of the vessel, underneath the flow path constrictions, will have a strong effect on the test results.

These three factors listed above show significant ways in which the HEDL tests fail to simulate the Darlington reactor vault. These failures introduce unquantified uncertainties in applying the HEDL test data to estimating the hydrogen combustion hazard in a Darlington power plant.

1.2 Scaling Concentration Fields

How can the concentration data obtained at HEDL be used for a Darlington safety analysis? There are several issues:

1. What was measured at HEDL?

2. How should this data be scaled?

3. Were significant concentration differences observed?

1.2.1 Measurements at HEDL

It is very important to note that the actual gas (helium) concentrations were not measured. As reported in Ref. 1, p. 4-9, the steam was removed from the gas sample before the helium concentration was measured and only the "dry basis" mole fractions were reported. As discussed below, it is the individual species concentrations (moles/m^3), or in the case of a dilute mixture, the mole fraction of the total mixture that should be scaled. While "dry basis" concentrations are easiest to measure; they cannot be used to accurately assess mixing.

In order to compute true concentrations, it is necessary to know the complete gas composition and the thermodynamic state; this information was not measured in the HEDL tests. There is a brief discussion on pp. 7-5, 7-6 of Ref. 1 of the effect of steam, but it is necessarily speculative since that actual steam concentration was unknown. The problem of determining the steam concentrations after the fact is very difficult due to the coupled nature of the heat and mass transfer due to condensation of the heated steam on the cool test vessel.

As discussed in Ref. 2, concentrations fields of two configurations will be similar (defined exactly below) if the geometrical configurations are exactly in proportion, and the nondimensional parameters Fr, Re, and Sc (Froude, Reynolds, and Schmidt numbers) that characterize the problem are all identical. As mentioned above, this is almost certainly not the case in comparing the HEDL test to the reactor vault at Darlington.

If there is geometric and flow parameter similarity, then the nondimensional transport equation for the binary diffusion of species a (helium-steam mixture) into species b (air) can be written as[2]

$$\frac{Dx^*}{Dt} = \left(\frac{\partial}{\partial t} + \mathbf{u}\cdot\nabla\right)x^* = \frac{1}{ReSc}\nabla^2 x^*$$

where $\mathbf{u}$ is the scaled mass-average velocity of the mixture, and x^* is the reduced mole fraction of species a

$$x^* = \frac{x_a - x_o}{x_i - x_o}$$

and x_i is a characteristic maximum mole fraction of species a and x_o is a characteristic minimum mole fraction of species a. In the jet mixing problem, x_i will be the mole fraction of helium (or hydrogen) in the jet and x_o will be the initial fraction in the containment or test vessel, which is zero.

This type of nondimensional scaling is frequently used to express data on turbulent mixing in other problems involving jets, plumes and stirring in containers[3]. As an example we cite the results for turbulent jets, a review of the data from many sources can be found in Ref. 4 The mean concentration $\bar{c}$ of a component of the nozzle fluid measured on the centerline of the jet (in the far field, $x/d_j > 10$) is found to scale

linearly with the initial concentration in the jet c_j, the jet diameter d_j and inversely on downstream distance

$$\frac{\bar{c}}{c_j} = 5.7 \left(\frac{\rho_j}{\rho_\infty} \right)^{\frac{1}{2}} \frac{d_j}{x}$$

The square root of the density ratio is needed to yield the correct scaling for variable density flows[4]. This scaling has been confirmed extensively for many different types of jet and atmosphere fluids and demonstrates the correctness of the approach outlined above, in which the spatial differences in concentration should be scaled with the reference level, the initial concentration in the jet fluid.

This scaling also applies to the radial profile of mean concentrations and the axial profile of concentration fluctuations. In the downstream portion of a jet ($x/d_j > 100$), r.m.s. concentration fluctuations on the jet centerline are found to be between 20 and 30% of the local mean centerline concentration.

In conclusion, if the data from HEDL were to be applied to another problem, *nondimensional* concentrations should be computed and scaled to predict the corresponding values for another facility. This scaling is carried out below for the HEDL tests.

1.2.2 Concentration Differences

Substantial spatial concentration differences did exist in the HEDL tests although they were played down in the discussion of the results given in Ref. 1. The differences are shown in Figs. 7-1 and 7-2 of Ref. 1 (reproduced below) and can also be obtained from the Gas Analyzer tabulation in Appendix G of Ref 1. These differences are not obvious from the plots of mean concentration shown in Chapter 6 of Ref. 1, but are nevertheless real.

The discussion given above on scaling indicates that the helium concentration-related variables should all be scaled by the value in the jet, approximately 12.5%, to obtain a nondimensional concentration. I have analyzed the data given in Ref. 1 and list in Table 1 the maximum spatial difference in concentration, the scaled value, the peak concentration, and the final value measured. The scaled maximum spatial variations range between 12 and 59%. Recall that these are all "dry basis" values and as such, do not represent the true concentrations. They would correspond to the concentration variations obtained if a pure hydrogen (or helium) jet were injected into the vessel. A 50% hydrogen jet (the rest being steam) would have one-half these values and so forth for other values of jet concentration.

1.2.3 Completeness and Consistency

Were the HEDL tests complete and consistent?

Without independent measuring techniques and samples unbiased by the removal of steam, it is difficult to judge the accuracy of the concentration measurements in the

Table 1: Helium Concentration Analysis for HEDL tests

Test	ΔX_{max}	X_j	$\Delta X_{max}/X_{jet}$	X_{max}	X_{final}
HM-1	4.0	12.0	33.0	13.5	3.1
HM-2	8.0	13.6	59.0	27.4	6.1
HM-3A	1.5	12	12.5	5.2	3.2
HM-4C	3.0	12.5	24.0	10.6	6.2
HM-6	1.8	12.5	14.4	7.1	3.3
HM-7	2.5	15.2	16.4	11.0	6.1

tests. Experimental results and numerical simulations reported in Ref. 5 do show similar trends in the concentration *vs* time profiles. Simple checks on the overall mass balance show that the experimental results are consistent on a basic level. For example, computing the mass of helium injected for HM-7 and the initial mass of the atmosphere indicates that the final concentration measured was correct.

The HEDL tests were very specific to the US Ice Condenser plant and a specific type of accident. They were never intended to be generic mixing tests that would be used to assess hydrogen transport in a wide variety of reactor containments. Given this limited scope, they cannot be considered as providing a good basis for evaluating hydrogen transport and mixing for very different plants such as the Darlington design. From this broader perspective, these tests cannot be considered as complete and the users of this data should be very cautious in applying it to other plants.

1.2.4 Further Testing

There were several problems with the HEDL data that indicate, together with the failure in geometric and flow parameter scaling, that the test should be redone specifically for the Darlington reactor vault if the problem of hydrogen mixing is considered a serious issue. These problems are:

1. Vessel geometry not similar enough to Darlington reactor vault

2. Inadequate exploration of source parameters (Froude number, location)

3. Steam not measured, "dry basis" concentrations only reported.

In redoing these tests, it would be acceptable to use another inert diluent (nitrogen or air) instead of steam and measure the true concentrations. Steam tests should be avoided, although they seem much more realistic, they are too difficult to interpret.

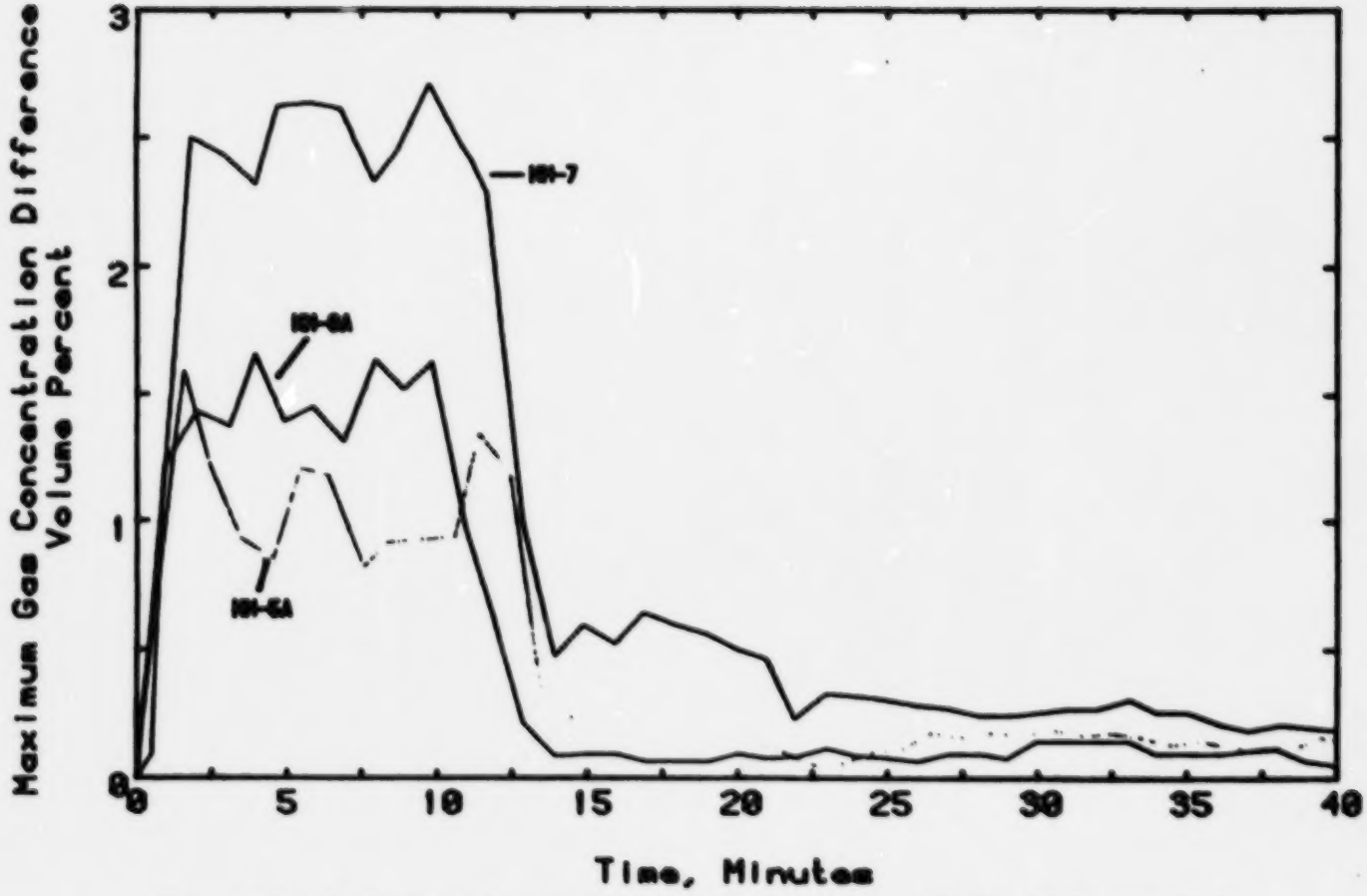


Figure 7-1. Maximum Gas Concentration Difference For Test HH-3A, HH-5A, and HH-7

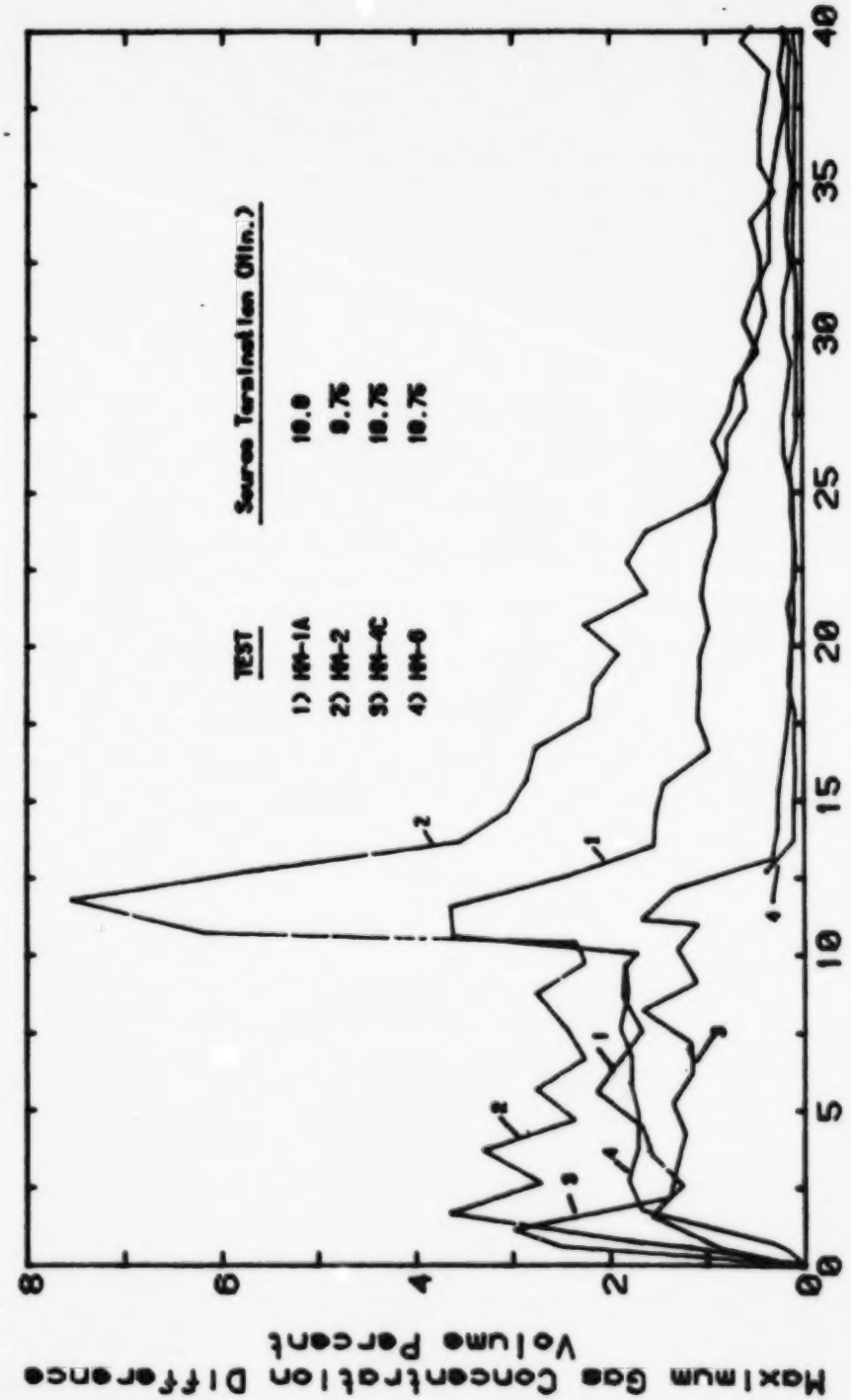


Figure 7-2. Maximum Gas Concentration Difference For Test HM-1A, HM-2, HM-4C, and HM-6

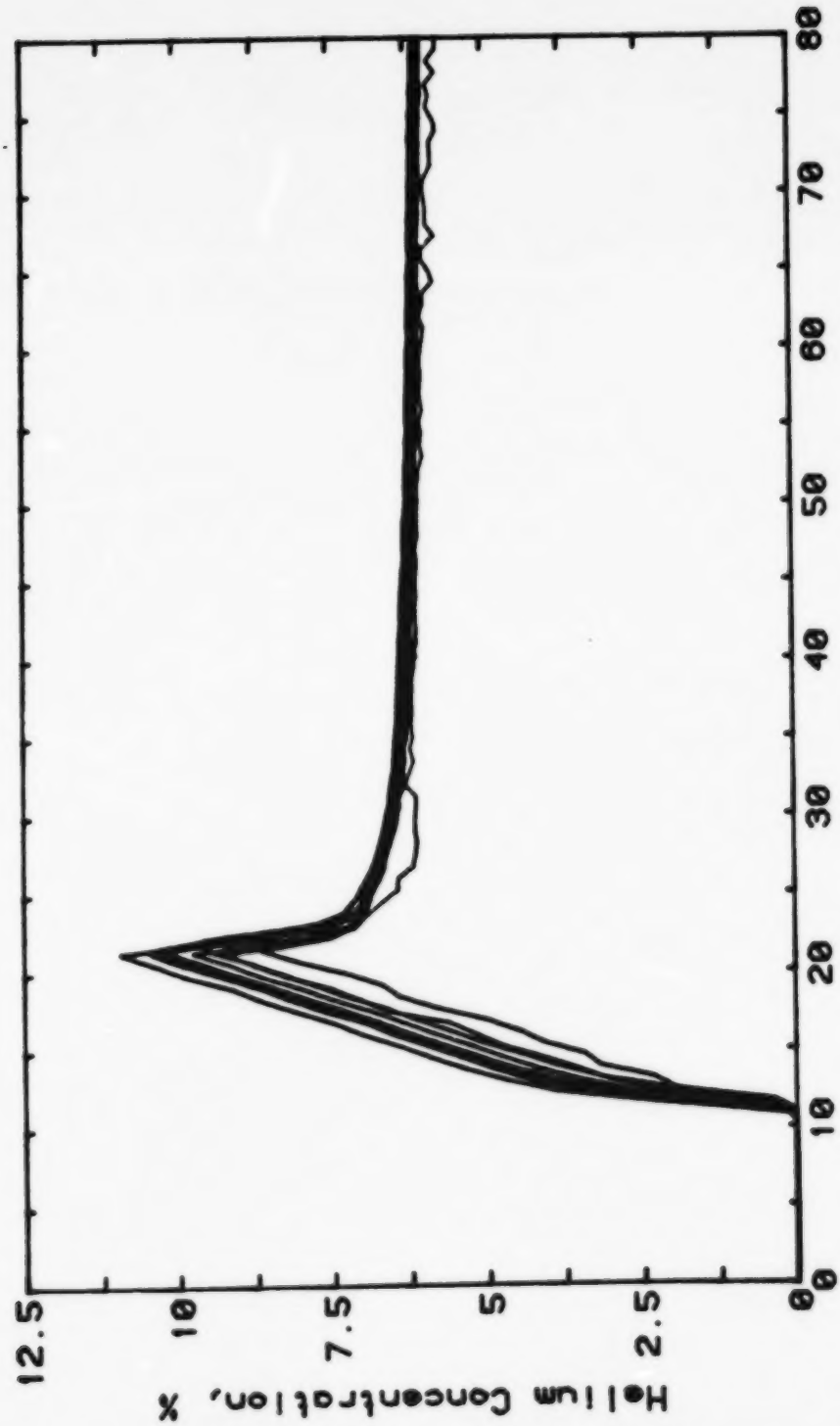


Figure 6-19. Test: HM-7 Helium Concentration

References

1. Anonymous, *Hydrogen Mixing and Distribution in Containment Atmospheres*, Electric Power Research Institute Report NP-2669, Project 1932-8 Final Report, March 1983.

2. R. B. Bird, W. E. Stewart, and E. N. Lightfoot, **Transport Phenomena**, Wiley 1960. Particularly pp. 580-583 and the references given therein.

3. J. E. Shepherd *Analysis of Diffusion Flame Tests*, Sandia National Laboratories Report SAND86-0419, 1987.

4. C. J. Chen and W. Rodi **Vertical Turbulent Buoyant Jets: A Review of Experimental Data**, Pergamon, 1980.

5. *Proceedings of the Second International Conference on the Impact of Hydrogen on Water Reactor Safety*, Sandia National Laboratories Report SAND 82-2456, October 1982. Especially see pp. 451-553.

APPENDIX B

FORMATION OF AN EXPLOSIVE FOOTPRINT BY THE RELEASE OF HYDROGEN IN AN INTENSE TURBULENT JET

R. Knystautas
McGill University, Montreal

Sample Calculation

Assume a 5 $cm\ dia$ rupture in which H_2 at a pressure of 20 atm ($\sim$ 300 psi) is driven into ambient air at 1 atm (101.3 kPa). The jet will be choked (sonic jet) and the exit conditions will be underexpanded so that the jet will further flare out supersonically from an exit diameter D_o to an effective diameter D_e. If in the present case $D_o = 5\ cm$ and $p_o/p_a \approx 20$, then $D_e/D_o \approx 3$.

The length of the 12% H_2 and 60% H_2 concentration footprints can immediately be calculated from

$$L_{12} = \frac{12.6\, r_e}{C_{12}} \approx 8\, M$$

$$L_{60} = \frac{12.6\, r_e}{C_{60}} \approx 1.6\, M.$$

From jet growth laws it can easily be shown that the maximum width of the footprint (B_{max}) is approximately one tenth of the length. So $B_{12_{(max)}} \approx 0.8\, M$ (see illustration Figure 1).

It is very easy to determine roughly the volume of the explosive footprint (neglecting the 60% H_2 contour).

$$V_{12} \approx 2\, M^3$$

The mass content of hydrogen in the footprint can roughly be determined from the partial pressure according to mole fraction

$$p_a = p_{air} + p_H$$

Then from the equation of state

$$pv = mRT$$

the mass of hydrogen m can be calculated. Taking a mean concentration between 12% h_2 and 60% H_2 and $T \approx 300°K$ with $R = 4.124\ kJ/kg°K$ one gets

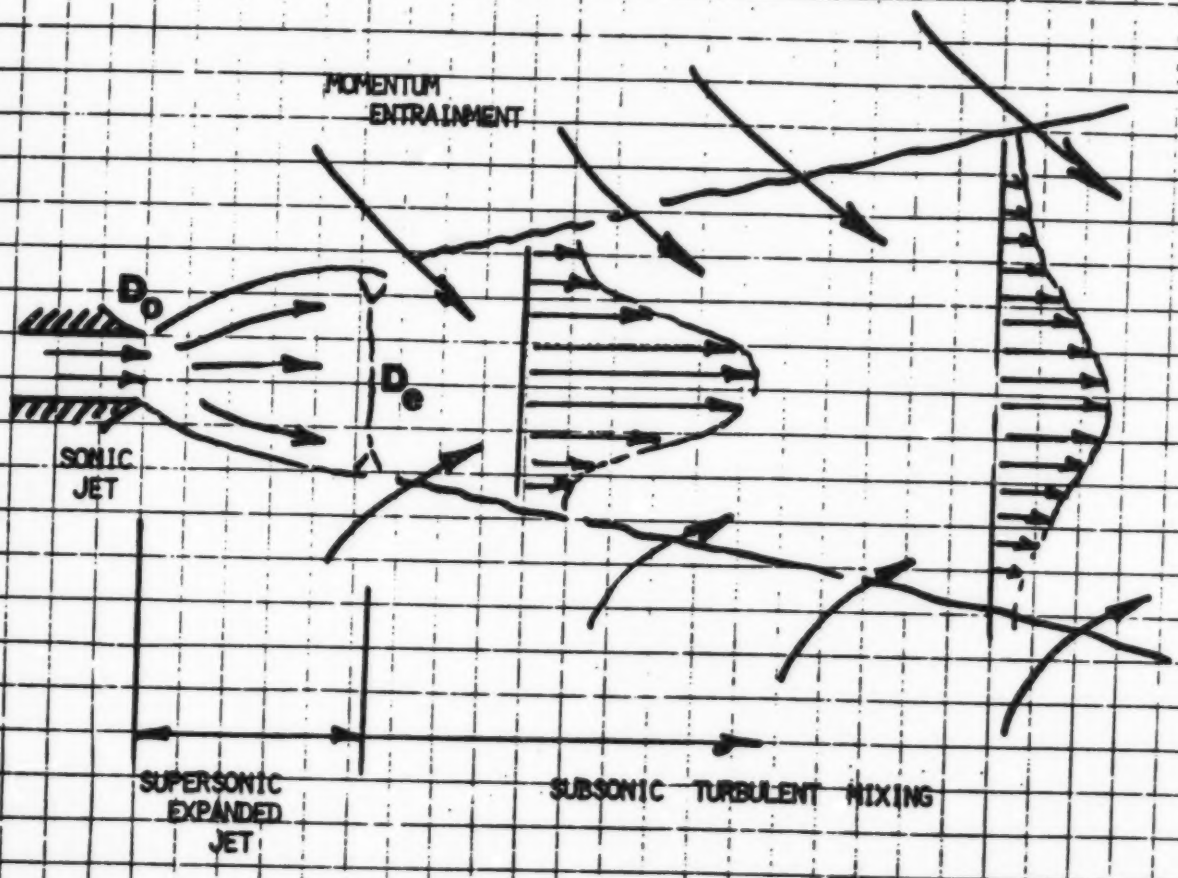
$$m_{H_2} \approx .05\ kg\ H_2.$$

The energy (heating value) of a fuel-air mixture for hydrogen-air is about $120\, MJ/kg$ fuel. Thus the energy content in the 12% H_2 footprint is about $6\, M\ Joules$. The heat of detonation of TNT is about $4.187\, MJ/kg$. Thus if the hydrogen footprint were to detonate, the energetics would be equivalent to about

$$TNT_{equivalent} = \frac{6}{4.187} = 1.4\ kg \text{ of TNT.}$$

It is to be noted that if the hydrogen source diameter went up by a factor of two, then the volume, the mass of hydrogen and the TNT equivalent would go up by the cubic power or a factor of eight.

EXAMPLE: EXPLOSIVE FOOTPRINT PURE HYDROGEN RELEASE FROM A 5 CM DIA PIPE IN A SONIC JET



MOMENTUM MIXING OF A TURBULENT JET

Heat of Combustion of Combustible Gases Involved In Vapor Cloud Accidents
[Adapted from Eichler and Napadensky (1977)]

Material	Formula	Low Heat Value (MJ/kg)	e_{HC}/e_{TNT} *
Paraffins			
Methane	CH_4	50.00	11.95
Ethane	C_2H_6	47.40	11.34
Propane	C_3H_8	46.40	11.07
n-Butane	C_4H_{10}	45.80	10.93
Isobutane	C_4H_{10}	45.60	10.90
Alkylbenzenes			
Benzene	C_6H_6	40.60	9.69
Alkylcyclohexanes			
Cyclohexane	C_6H_{12}	43.80	10.47
Mono Olefins			
Ethylene	C_2H_4	47.20	11.26
Propylene	C_3H_6	45.80	10.94
Isobutylene	C_4H_8	45.10	10.76
Miscellaneous			
Hydrogen	H_2	120.00	28.65
Ammonia	NH_3	18.61	4.45
Ethylene Oxide	C_2H_4O	26.70	6.38
Vinyl Chloride	C_2H_3Cl	19.17	4.58
Ethyl Chloride	C_2H_5Cl	19.19	4.58
Chlorobenzene	C_6H_5Cl	27.33	6.53
Acrolein	C_3H_4O	27.52	6.57
Butadiene	C_4H_6	46.99	11.22
HC Groups (est)	———	44.19	10.56

* Based on a heat of detonation of 4187 kJ/kg for TNT, which differs from the experimental value reported earlier in this chapter.

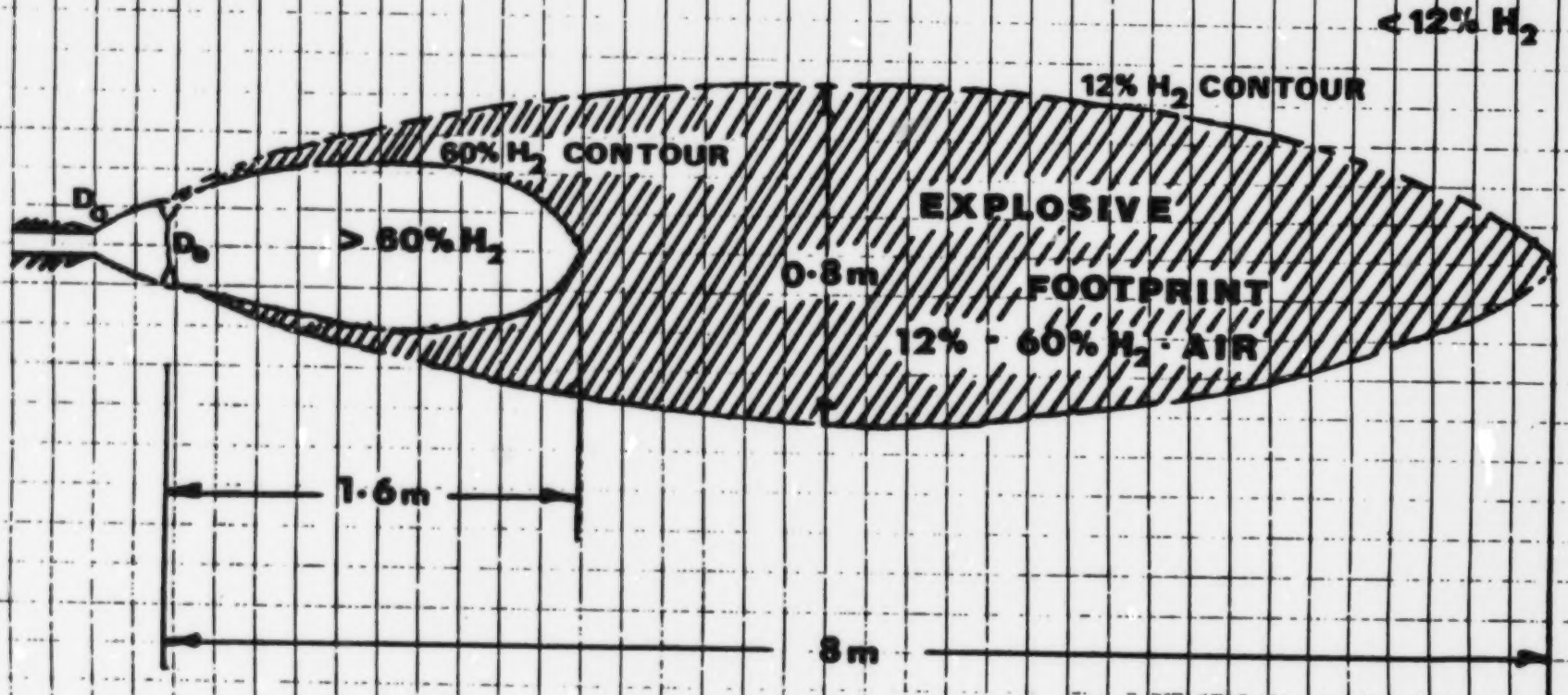

< 12% H_2
12% H_2 CONTOUR
60% H_2 CONTOUR
D_0
D_0
> 60% H_2
EXPLOSIVE
FOOTPRINT
12% - 60% H_2 - AIR
0·8m
1·6m
8m

FIG - 1

APPENDIX C

ACCOUNT OF INDUSTRIAL ACCIDENTS INVOLVING HYDROGEN RELEASE AND SUBSEQUENT IGNITION

J.H. Lee
McGill University, Montreal

MEMORANDUM

TO: NUREG-1150 Containment Loading Expert Review Panel
FROM: J.H.S. Lee
SUBJECT: Possibility of Ignition of H_2 DATE: Feb. 16, 1988

Regarding the possibility of ignition of hydrogen-air mixtures which might be present during reactor accidents, I feel that ignition is almost a certainty if the hydrogen release rate is sufficiently rapid even if there are no obvious ignition sources present. Ignition sensitivity (as measured by the minimum ignition energy) is a function of H_2 concentration, minimum value at about the stoichiometric value. The spark energy is typically a fraction of a millijoule. In a release, if the mixture prior to release is hydrogen rich, then it can be expected that in the mixing zone of the jet there will be a region in which the H_2 concentration is near stoichiometric. A spark from static electricity will most probably cause ignition. Reviewing actual accidents seems to support my conclusion. Apart from the well known accident at NASA White Sand Test Facility (Jackass Flat incident), there are three recent accidents I know of that resulted not only in ignition but detonation as was deduced from the fatalities and the nature of the blast damages.

1. In April 1984, an accident happened at Polysar, Sarnia in Ontario, Canada. The gasket of a large pipe blew, releasing an estimated total amount of 15 to 30 kg of H_2 into the atmosphere in about $15 - 20$ sec. The pressure in the pipe is about 600 psi. No obvious ignition source is present, the cloud is unconfined. Ignition followed by deflagration to detonation transition (DDT) and detonation occured. Significant blast damages with 2 fatalities.

2. In 1985 in Norway, a Norske Hydro plant had a similar unconfined H_2 vapor cloud detonation. The gasket of a pipe blew releasing a gas 40% H_20 and 60% CO_2 (saturated with H_2) into the atmosphere. The pressure in the pipe is about 200 psi. The estimated amount of H_2 released is about 15 kg. The time of the release prior to the explosion is not known because both workers died. No obvious ignition source around, and it is suspected that a hot bearing nearby might be the cause of ignition.

3. In Arkansas in 1986, an ammonia plant had a serious vapor cloud. The gas released into the atmosphere consisted of $\frac{2}{3}$ H_2 and $\frac{1}{3}$ N_2. The end of a horizontal heat exchanger blew. It was 2400 psi in the heat exchanger whose diameter is 32" and the end flange is 9" thick. The estimated amount of the release was 15 to 30 kg and the duration is about 10 sec before explosion. No obvious ignition source is present. The cloud is unconfined (but high turbulence from obstruction is present) and DDT must have occured judging from the severity of the blast damages.

Of course only the serious accidents have been reported, there may be numerous small leaks that are not reported. However, talking to people working in the plant, they admit that any leak of H_2 always results in ignition and a fire. Compared to hydrocarbon release, hydrogen appears to be much more probable to self ignite. When it does, it is also highly prone to DDT. I do think if the H_2 concentration prior to release is higher than the flammability limit and if the release rate is also high, I would estimate the probability for ignition to be unity.